DEPARTMENT OF COMMERCE
LEWIS L. STRAUSS, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 86
Number 11

NOVEMBER 1958

Closed January 15, 1959
Issued February 15, 1959

FORECASTING STRONG WINTER WINDS OVER PUERTO RICO AND THE VIRGIN ISLANDS

HARRY M. HOOSE AND ROBERT LEVINE

U. S. Weather Bureau, San Juan, Puerto Rico

[Manuscript received April 25, 1958; revised September 4, 1958]

ABSTRACT

Wintertime synoptic situations leading to the occurrence of strong surface winds over coastal waters of the Dominican Republic, Puerto Rico, the Virgin Islands, and the northern Leeward Islands are discussed. Six-hourly average wind speeds for the oceanic areas adjacent to Puerto Rico are obtained from ship reports and related to the surface pressure gradient. The onset of surface winds of 20 knots or greater is found to follow the crossing of the east coast of the United States by a migratory anticyclone with above critical central pressure, or the occurrence of strong trade winds above the gradient level at San Juan, P. R., as a nonmigratory anticyclone intensifies. These results are combined into objective forecasting rules for predicting the onset of strong winds 12 to 24 hours ahead.

1. INTRODUCTION

Sailing schooners and small motor vessels engage in commerce between Puerto Rico and the Lesser Antilles amounting to more than $13 million annually. Warnings for strong winds and rough seas are important in protecting these small craft as well as fishing and pleasure boats. This study develops a procedure for predicting the onset of strong winds sufficiently in advance so that warnings may be issued and distributed in time to be effective. The study is limited to the winter months and to a forecast area bounded by the parallels 17° and 22° N. and the meridians 60° and 70° W. (fig. 4). This area includes the adjacent waters of the Dominican Republic, Puerto Rico, the Virgin Islands, and northern Leeward Islands for which Small Craft Warnings are issued. Forecasting strong winds over this area presents a problem due to the lack of reliable surface wind reports and sparsity of data over critical oceanic areas.

Initially, the study is concerned with the relationship between wind and pressure gradient over the forecast area. After determining this relationship the study concentrates on the pressure gradient and uses it as a measure of the wind strength. Finally, the study derives an objective method for forecasting the onset of strong winds 12 to 24 hours from the time of the latest synoptic surface map.

Past experience indicates that strong winds over the forecast area in winter are usually caused by intense high pressure systems to the north. Deep Lows in the western North Atlantic usually move on a track too far north to cause strong winds in the forecast area; however, swells generated by these storms occasionally do reach the area. Strong winds of short duration may be caused by thunderstorms, but these are rare in winter and are not treated in this paper. Thus the only significant synoptic situation likely to cause strong winds in the winter is related to a high-pressure system centered north of the forecast area. Anticyclones most likely to create strong winds in the forecast area may be divided into two types. These are migratory cold Highs moving eastward off the coast of the United States and semipermanent warm Highs over the western North Atlantic.

In marine terminology a strong wind is equivalent to Beaufort Force 6 (22 to 27 knots) and Small Craft Warnings are issued whenever this condition is expected in the forecast area. Although the lower limit of a strong wind by this definition is 22 knots, this study uses 20 knots since ship reports, which constitute the main source of surface wind data, are entered on the surface map to the nearest 5 knots.

2. SELECTION OF DATA

SURFACE WIND

Land stations with representative surface wind reports would have greatly simplified the tabulating of data. Unfortunately, there are no land stations in Puerto Rico or the Virgin Islands that have an unobstructed exposure and that could be considered representative of the surface wind conditions over the open sea. The wind speed falls off very rapidly a short distance inland from the coast because of friction, land and sea breeze effects, and terrain and vegetation. For example, on January 21, 1957, when ship reports in the vicinity of Puerto Rico indicated winds of 20 to 25 knots, an anemometer mounted on a mast 76.7 feet above sea level at the Naval Air Station in San Juan recorded winds of 5 to 10 knots with a maximum of 16 knots. On the same day, Isla Verde Airport to the east of San Juan recorded winds that generally ranged between 5 and 12 knots with a maximum of 18 knots. It was therefore necessary to turn to ship reports to obtain reliable surface wind data for this study.

Representative surface winds were obtained by averaging ship reports in the forecast area (fig. 4). The area extends farther to the north than to the south of Puerto Rico because synoptic developments creating high winds during the winter almost invariably approach from the north. Data for the months December through March of 1955–56 and 1956–57 were used as the development sample. Wind speeds were averaged for each 6-hourly surface map during these periods whenever surface ship reports were available in the area. Great care was taken to ascertain that reports were representative of the wind field. This was done by checking the past history of ships for wind accuracy and by discounting ships' reports that were obviously in error. Data from maps having only one ship in the area were not tabulated when the data were obviously erroneous.

PRESSURE GRADIENT

After the surface wind data had been obtained, the next step was to measure the surface pressure gradient. This was measured by taking the pressure difference in millibars over the fixed distance of 10° of latitude from 15° N. to 25° N. along a north-south line across Puerto Rico. Because of the prevailing easterly wind flow in the Caribbean, a north-south line is almost always perpendicular to the isobars. The reason for choosing this distance with its longer segment lying north of Puerto Rico was to emphasize the data to the north of the island. Before this particular measurement of the gradient was selected, alternative measurements that attempted to make full use of available land stations had proved unsatisfactory.

Pressure gradient measurements over the selected distance were taken from each 6-hourly surface map for the winters of 1955–56 and 1956–57. This pressure gradient, hereafter designated by Δp, was measured independently of the surface wind speed to eliminate, as far as possible, the introduction of bias. Measurements of Δp by different forecasters varied by less than 1 millibar; pressure readings at latitude 15° N. were considered to be very reliable in view of the pressure observations at land stations in the Lesser Antilles; readings at 25° N., being farther away from land were more subjective, but nevertheless were fairly reliable due to the averaging effect of numerous ship reports.

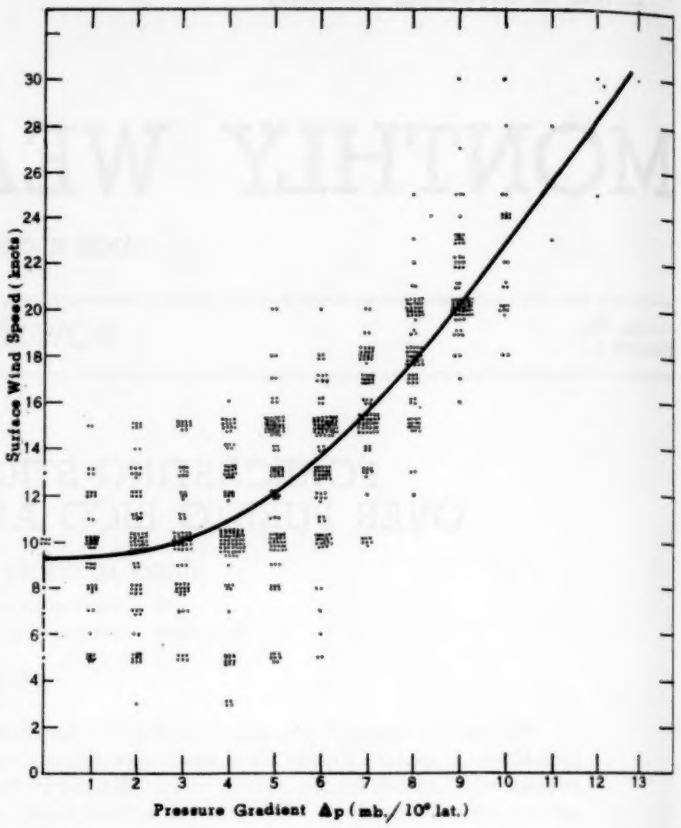


FIGURE 1.—Scatter diagrams showing correlation between pressure gradient (Δp) and surface wind speeds for winters of 1955–56 and 1956–57.

3. RELATION OF PRESSURE GRADIENT TO THE SURFACE WIND

Figure 1 shows the relationship of the pressure gradient (Δp) to the surface wind speed based on data for the winters 1955–56 and 1956–57. The direct correlation between Δp and surface wind speed is well marked. As an example, $\Delta p=3$ corresponds in general to a surface wind speed between 8 and 13 knots, $\Delta p=8$ corresponds to 15 to 20 knots, and $\Delta p=10$ corresponds to 20 to 25 knots.

A value of 20 knots was selected as the critical wind speed requiring Small Craft Warnings in the forecast area. Figure 1 shows that $\Delta p>8$ almost always results in surface wind speeds of 20 knots or greater. This can be more readily seen in figure 2 which shows that—

- $\Delta p\geq 9$ corresponds to speeds of 20 knots or greater 88 percent of the time;
- $\Delta p\leq 7$ corresponds to speeds of less than 20 knots 99 percent of the time; and
- $\Delta p=8$ is marginal corresponding to speeds of 20 knots or higher 33 percent of the time.

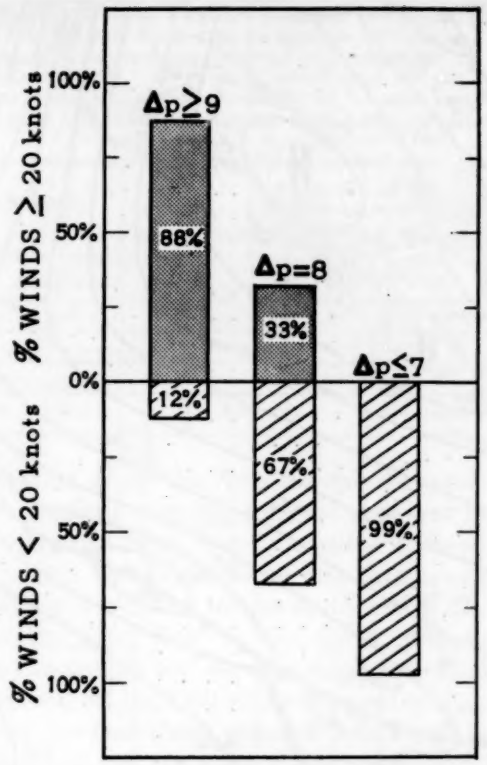


FIGURE 2.—Percentages of surface winds above or below 20 knots for various pressure gradients (Δp).

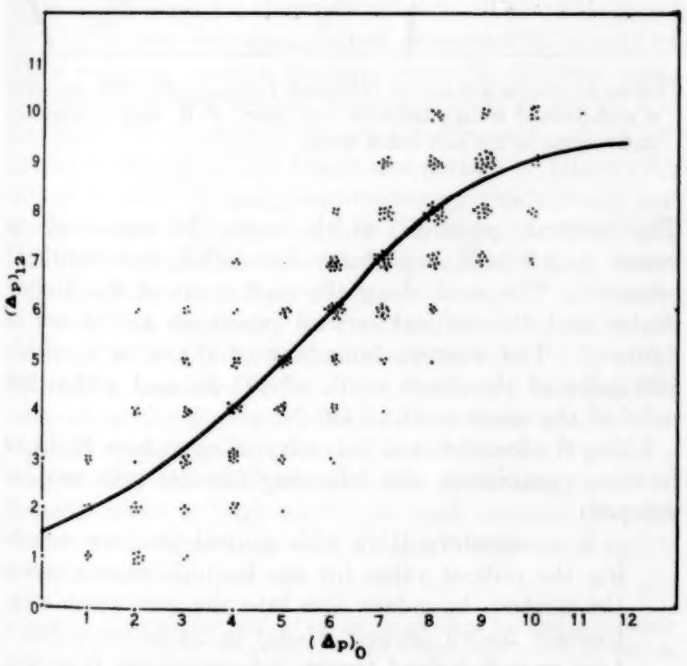


FIGURE 3.—Scatter diagram showing relationship between current pressure gradient $(\Delta p)_0$ and pressure gradient 12 hours later $(\Delta p)_{12}$ for winter 1956–57.

Thus, with $\Delta p \geq 9$, Small Craft Warnings are necessary and for a $\Delta p \leq 7$ no warnings are needed. Occasions when winds of 20 knots or higher occurred with $\Delta p = 8$ were investigated separately. For these occasions, if in conjunction with semipermanent Highs, the upper winds provided a worthwhile forecast parameter. This is discussed in section 6.

To determine the persistency of a given pressure gradient, scatter diagrams were plotted for current Δp against its value 6, 12, 18, and 24 hours later. The scatter diagram for a 6-hour lag showed that Δp would not vary by more than 1 millibar. The scatter diagram for a 12-hour lag (fig. 3) also shows good correlation and that the 12-hour change in Δp rarely exceeds 2 millibars. This slow change in Δp normally precludes the sudden occurrence of gradients associated with strong winds.

4. SELECTION OF FORECAST PARAMETERS

As previously stated, the forecast problem is to predict the onset of strong winds over the forecast area in time to issue early warnings. Forecasts much beyond 24 hours are generally unnecessary, and forecasts for less than 6 hours provide too little time to issue warnings. Therefore, it was decided to concentrate this study on a forecast for a minimum of 12 hours, and preferably for 24 hours, subsequent to the time of the latest surface map. Subject to these requirements, the first step was to select parameters for a forecast method to be valid for the months of December through March.

Parameters selected for the forecast study were those that seemed most successfully to measure conditions causing the onset or continuance of strong winds over the forecast area. These were: (1) location and intensity of migratory Highs, and (2) pressure gradient (Δp) and upper winds associated with semipermanent Highs. Several other parameters were investigated, but proved of little value in improving the forecast method. These included 24-hour pressure changes in the Caribbean, temperature difference between 1000 and 850 mb., and the gradient wind over San Juan, P. R.

5. FORECAST SYSTEM FOR MIGRATORY HIGHS

DEVELOPMENT OF SYSTEM

Since migratory Highs affecting Puerto Rico almost invariably move off the east coast of the United States, the position and intensity of these Highs as they crossed the coastline and the subsequent winds in the forecast area were investigated. Migratory Highs were tested in the following manner: (1) all surface maps for the winters of 1955–56 and 1956–57 were reviewed and the track and central pressure were plotted for every migratory High moving off the east coast of the United States (2) the valve of Δp (measured between 15° N. and 25° N.) on each synoptic map was plotted beside the corresponding position of the migratory High; (3) the position of a migratory High that coincided with $\Delta p \geq 9$ 24 hours later was circled; and (4) a line was drawn through eastern United States just west of all these circled positions. This line, together with the coastline, delineated an area of the United States where migratory Highs had the potential of creating $\Delta p \geq 9$. It also gave the central

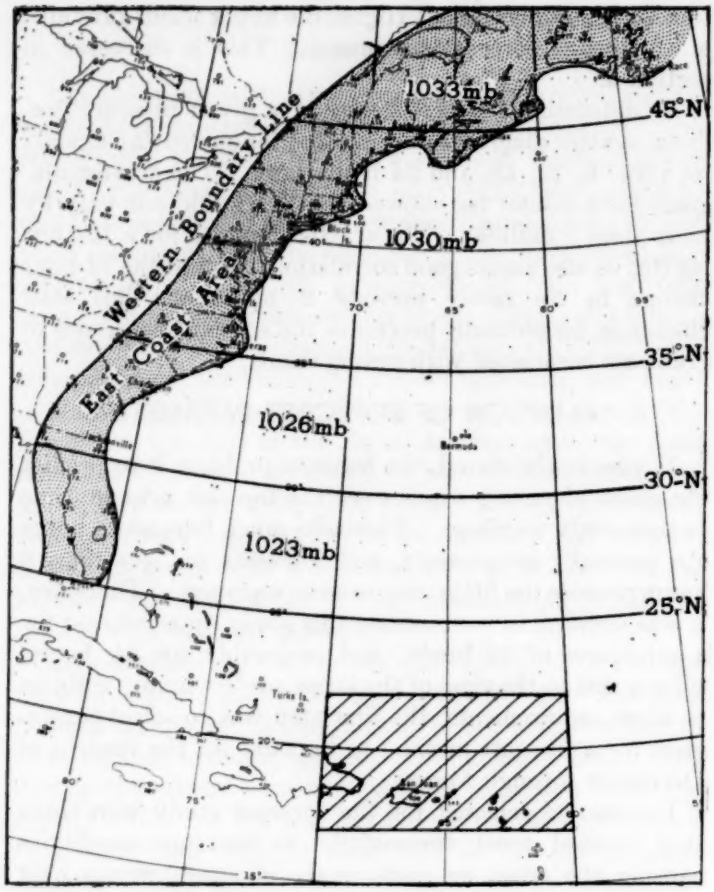


FIGURE 4.—Map showing east coast area (shaded) and the critical central pressure for Highs, by latitude zones, which must be exceeded to cause $\Delta p \geq 9$ over Puerto Rico in 24 hours. Hatched zone is area over which surface ship reports were averaged to obtain surface wind speeds and includes forecast area (Puerto Rico, the Dominican Republic, the Virgin Islands, the northern Leeward Islands, and the adjacent Caribbean and North Atlantic waters).

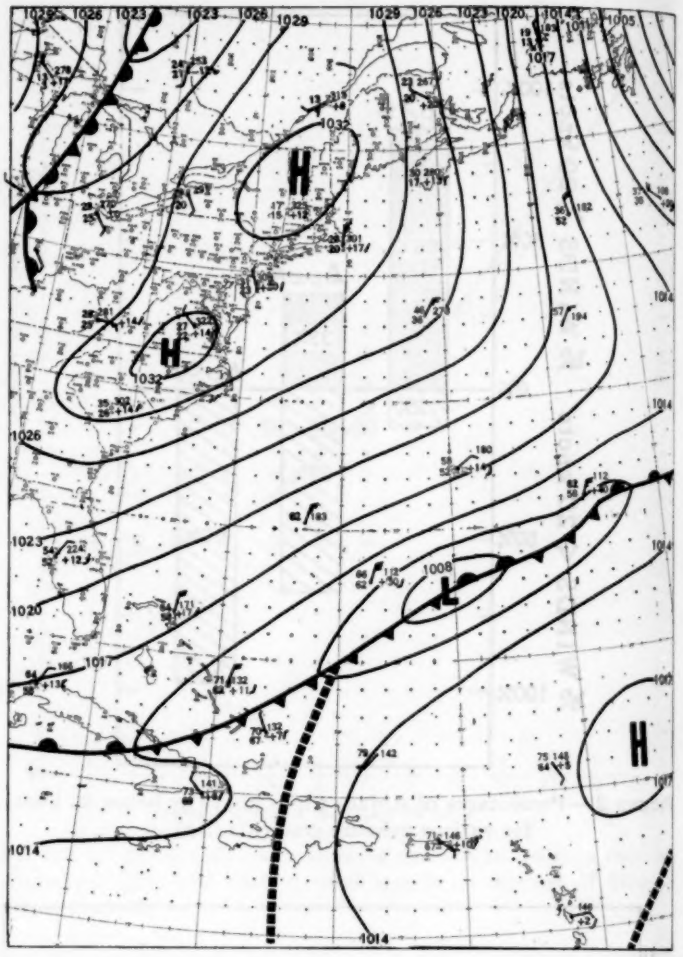


FIGURE 5.—Surface chart for 1200 GMT, February 22, 1957, depicting a well-defined trough between San Juan, P. R., and a migratory anticyclone in the east coast area.

pressures responsible for the eventual tightening of the gradient over the forecast area. James [1] has computed the mean central pressure of anticyclones over North America according to latitude. Table 1 shows that central pressures of anticyclones that eventually caused $\Delta p \geq 9$ were slightly higher than this mean and that the chances of a migratory High causing $\Delta p \geq 9$ depended on its intensity and latitude. The farther south the center is located, the weaker the High can be and still cause $\Delta p \geq 9$, and conversely, the farther north the center, the greater the central pressure has to be to produce $\Delta p \geq 9$.

TABLE 1.—*Central pressures of anticyclones at various latitudes*

Latitude (°N.)	Mean central pressure as computed by James [1] (mb.)	Central pressure which must be exceeded to cause $\Delta p \geq 9$ (mb.)
25–30	1023.5	1023
30–35	1024.5	1026
35–40	1026	1030
40–45	1027	1030
45–50	1028.5	1033

The central pressure which must be exceeded to cause $\Delta p \geq 9$ will henceforth be called the "critical" pressure. The area along the east coast of the United States and the critical central pressures are shown in figure 4. The western boundary of the area is within 200 miles of the coast south of 40° N. and within 250 miles of the coast north of 40° N.

Using the location and intensity of migratory Highs as forecast parameters, the following forecast rule was developed:

> If a migratory High with central pressure exceeding the critical value for the latitude moves across the western boundary line into the east coast area, forecast $\Delta p \geq 9$ (strong winds) in 24 hours unless a Low or well-defined trough is between the High and Puerto Rico.

Location and intensity of migratory Highs were used to forecast Δp rather than winds directly because of the deficiency of wind data on many charts. It has already been established that the pressure gradient may be used as a measure of the wind strength.

Cases where a low-pressure area or a well-defined trough was located between the high center and Puerto Rico

TABLE 2.—*Relationship of central pressures and latitude of migratory Highs entering east coast area in winters 1955–56 and 1956–57 to occurrences of pressure gradients $\Delta p \geq 9$ between 15° N. and 25° N. across Puerto Rico. x=cases in which High did not cause $\Delta p \geq 9$; numbers=time in hours to reach $\Delta p \geq 9$; *=cases in which Low or well-defined trough existed between high-pressure area and Puerto Rico*

Latitude (° N.)	Central pressure (mb.)				
	≤1023	1024–1026	1027–1030	1031–1033	≥1034
45–49	x		xxx	xxxx	30, 24, 12, 24
40–44	x		xx	*, 24	24, 36, 24, *
35–39	x	xxxxx, 18	xxx		x, 30
30–34	x	xx	x, 24		24
25–29	x	x, 24			

were excluded from the forecast rule because in those cases the gradient over the forecast area was not caused by the migratory High, but by another system. A well-defined trough was taken to be one with a southerly to southwesterly wind flow to the south and a northerly to northeasterly wind flow to the north. Figure 5 illustrates such a trough and shows a migratory High moving northeastward off the United States coast while the circulation over the Caribbean remains dominated by a semi-permanent high cell centered in the mid-Atlantic.

EVALUATION OF SYSTEM

Results of the forecast rule for migratory Highs applied to the initial data are shown in table 2. This table shows the relationship between central pressures of migratory Highs entering various latitude zones in the east coast area (crossing the western boundary line in fig. 4) and the future development (or nondevelopment) of $\Delta p \geq 9$. Entries to the left of the heavy line pertain to Highs with critical or below critical pressures for a given latitude, and entries to the right of the heavy line pertain to Highs with above critical pressures for a given latitude. Times when the forecast rule verified are shown as "x" marks on the left of the heavy line and as numbers (hours to reach $\Delta p \geq 9$) on the right of the line. An "x" on the right and a number on the left of the heavy line indicate times when the forecast rule failed. As an example, a High entering the east coast area at 40° N. with a pressure between 1031 and 1033 mb. is shown as causing $\Delta p \geq 9$ in 24 hours, while a High at 25° N. with pressure of 1023 mb. or less is shown as an "x" mark indicating $\Delta p \geq 9$ never occurred.

TABLE 3.—*Contingency table of results of objective forecast procedures for migratory Highs for initial data (December 1955, 1956; January, February, March, 1956 and 1957)*

		Forecast		
		$\Delta p \geq 9$	$\Delta p < 9$	Total
Observed	$\Delta p \geq 9$	12	1	13
	$\Delta p < 9$	3	26	29
	Total	15	27	42
Percent correct: 90 Skill score: .79				

TABLE 4.—*Relationship of central pressure and latitude of migratory Highs entering east coast area in winters 1953–54 and 1954–55 to occurrences of pressure gradient $\Delta p \geq 9$ between 15° N. and 25° N. across Puerto Rico. Symbols as in table 2*

Latitude (° N.)	Central pressure (mb.)				
	≤1023	1024–1026	1027–1030	1031–1033	≥1034
45–49			x	x x	*, 24
40–44	x x x	x	x x x	18	24
35–39	x x	x x x x x x x	x x x x x x, 36	36, 36, 30 30, 30	24, 18
30–34	x x x x x x x x	x x	x	18, 24	12
25–29	x x x x				

Highs north of 50° N. and south of 25° N.are not entered in table 2 since none of these caused $\Delta p \geq 9$. In fact, very few migratory Highs occurred south of 30° N.; the majority moved off the east coast between 35° and 50° N. This agrees fairly well with results obtained by James [1] in a study of 2,955 migratory anticyclones identified on the 1230 GMT surface weather map for North America. He found only 2 percent of the anticyclones were centered between 25° and 30° N.; the majority (56.5 percent) were located in the zone between 35° and 50° N.

As shown by table 2, the most frequent time required for $\Delta p \geq 9$ to develop after a High with an above-critical central pressure moved across the western boundary line into the east coast area was 24 hours. The average time was 25 hours. Thus, the forecast rule based on migratory Highs proved most satisfactory for periods of 24 hours.

When placed in contingency table form (table 3), the initial data gave an accuracy of 90 percent and a skill score of 0.79. The proportion of occurrences of $\Delta p \geq 9$ correctly forecast was 92 percent.

Although these scores are good they are not a real test of the method. Table 4, arranged in the same manner as table 2, indicates the results obtained when the forecast rule for migratory Highs which was developed from the 8 months of initial data was applied to an additional 8 months for the winters of 1953–54 and 1954–55. Results of these independent test data were similar to those obtained from the initial data. The most frequent time required for $\Delta p \geq 9$ to develop over Puerto Rico after an anticyclone with above critical pressure entered the east coast area was 24 hours and the average time was 25 hours. When placed in a contingency table (table 5) these test

TABLE 5.—*Contingency table of results of objective forecast procedures for migratory Highs for test data (December 1953, 1954; January, February, March, 1954 and 1955)*

		Forecast		
		$\Delta p \geq 9$	$\Delta p < 9$	Total
Observed	$\Delta p \geq 9$	13	1	14
	$\Delta p < 9$	1	40	41
	Total	14	41	55
Percent correct: 96 Skill score: .90				

data showed an accuracy of 96 percent and a skill score of 0.90. The proportion of occurrences of $\Delta p \geq 9$ correctly forecast was 93 percent.

Since there were no official Small Craft Warning forecasts available for comparison with the results from the initial and independent data, a further 12-month test was made using Daily Series Synoptic Weather Maps, Northern Hemisphere Sea Level Charts published by the U. S. Weather Bureau for the winters of 1944–45, 1951–52, and 1952–53. Winters of 1951–52 and 1952–53 were selected to make a continuous coverage of six winters when taken with the previously analyzed initial and test data. The winter of 1944–45 was picked at random. As the synoptic maps in these series are spaced 24 hours apart, this was a good test of the forecast system. A few migratory Highs could not be used as their centers passed through the east coast area in the interval between maps. Testing the forecast system with these data resulted in 53 cases of migratory Highs, but 8 of these had to be discarded as there were insufficient data to determine the pressure gradient accurately. The remainder gave an accuracy of 91 percent correct forecasts with a skill score of 0.75 which is in good agreement with the results obtained from the initial data.

While the terms $\Delta p \geq 9$ and strong winds have been used synonymously, $\Delta p \geq 9$ did not correspond to winds of 20 knots or more 12 percent of the time (fig. 2). Although it is believed that much of this failure may be due to incorrectly read gradients or inaccuracies and sparcity of surface ship data, nevertheless the number of correct forecasts using the migratory High forecast system must be reduced by 12 percent in order to determine the accuracy of the system in forecasting the onset of strong winds within 24 hours. Reducing the results by this percentage gives an accuracy of 81 percent for the initial data and 82 percent for the test data.

To make the migratory High forecast system as objective as possible, no attempt was made to forecast the future track or change in intensity of high centers. An effort to link the intensities of Highs with the time interval before $\Delta p \geq 9$ was reached was unsuccessful. During the investigation of migratory Highs, however, it was noted that most failures of the forecast system were due to Highs intensifying or weakening as they moved off the east coast of the United States, or to a High moving across latitude zones with different mean pressures. Even though the skill score obtained by this objective forecast system is probably slightly higher than could be expected in day-to-day forecasting, use of a little forecasting skill in foretelling the change of central pressure of Highs as they move off the United States coast should further improve the accuracy of the system. In fact, the migratory High forecast system was used during the past winter season (1957–58) with excellent results. Forecasters appear to have the most difficulty with Highs that are close to critical intensity. To provide for such cases, the forecast rule was modified to the extent that if a migratory High has a near-critical central pressure, the forecaster should wait an additional 6 to 12 hours to make sure that the High does not change its intensity and at the same time watch the pressure gradient over the forecast area to determine the trend. Even with a delay of an additional 12 hours, there is still ample time left to issue warnings should they be required.

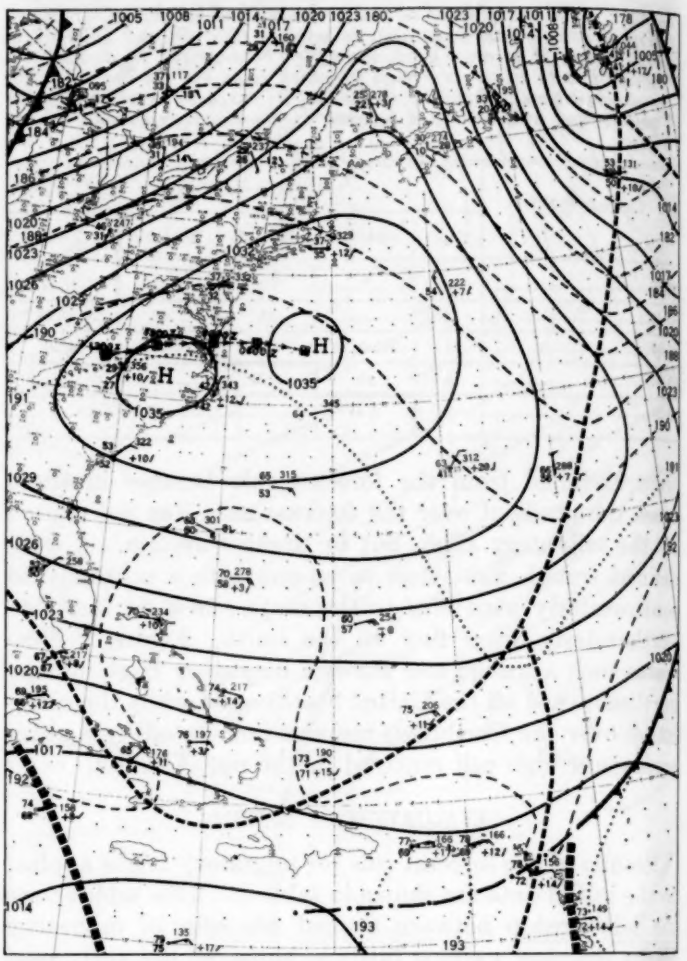


FIGURE 6.—Surface chart for 1200 GMT, December 23, 1957, depicting a migratory High with track of 6-hour past positions. 500-mb. chart for 1200 GMT, is superimposed as thin dashed lines.

6. FORECAST SYSTEM FOR SEMIPERMANENT HIGHS

DEVELOPMENT OF SYSTEM

Semipermanent warm Highs over the western North Atlantic may be due either to migratory cold Highs that gradually modify as they move over the relatively warmer area of the North Atlantic, or to the Azores High shifting to the west of its normal position. In either case, these Highs are normally centered south of 40° N. and west of 45° W. and create a strong gradient over the eastern Caribbean area as they intensify.

The basic difference between the migratory and semipermanent anticyclones is illustrated in figures 6 and 7. Figure 6 is a surface map of a typical migratory High after it crossed the United States coast and began to influence the eastern Caribbean; thin dashed lines show corresponding 500-mb. chart for the same date and time.

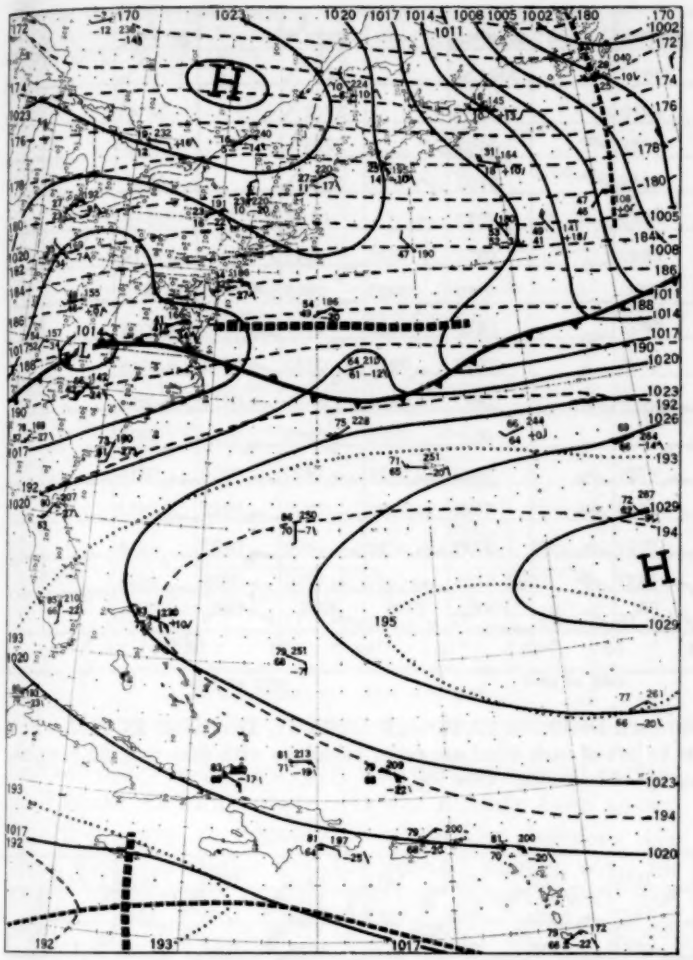


FIGURE 7.—Surface chart at 1800 GMT, February 1, 1957, showing a semipermanent anticyclone. 500-mb. chart for 1500 GMT, is shown by thin dashed lines. Note intense High corresponding to surface system.

It should be noted that the migratory High does not extend to the 500-mb. level as a well-defined closed center. Figure 7 is a surface map of a typical semipermanent High which has intensified north of the Caribbean. The corresponding 500-mb. chart is superimposed as thin dashed lines. This High is well marked at both the surface and 500 mb. and is quite intense aloft.

The trade winds over San Juan, P. R., as shown by Stone [2] are strongest between 750 and 1,000 meters (2,500 and 3,300 feet) and decrease downward due to surface friction. They also decrease upward until the westerlies are reached. This agrees with the observation of Riehl, Yeh, Malkus, and LaSeur [3] in the Pacific where wind speed decreased above and below the lower portion of the trade cumuli cloud layer (2,500 to 3,000 feet). However, an inspection of the upper winds at San Juan, P. R., revealed that there were occasions when strong surface winds were accompanied by increasing rather than decreasing upper winds above 3,000 feet. These occasions were investigated.

The upper wind parameter selected in this analysis was the maximum wind speed in the layer from 4,000 to 6,000 feet taken from the San Juan upper air data. This layer was above the normal trade wind maximum and proved satisfactory in showing those times when the trades increased rather than decreased above the 3,000-foot level. This parameter was tested only for $\Delta p=8$ since, as pointed out previously, $\Delta p=8$ is the only marginal pressure gradient. A stronger pressure gradient produces surface winds of 20 knots or more and a weaker gradient causes winds less than 20 knots. Little correlation was found between the upper wind parameter and the concurrent surface wind speed. However, when the upper wind parameter was compared with the surface wind speed 6, 12, 18, and 24 hours later, there was some correlation. The best correlation was in 12 hours.

It seemed logical to associate the times when the trade winds increased with intensification of semipermanent anticyclones in the western North Atlantic. Stone [2] pointed out that the axis of the Azores High slopes from northeast to southwest so that the northward shift of the High with the approach of summer has the effect of lifting the base of the westerlies. Consequently, in winter the base of the westerlies is low due to the southward shift of the Azores High. The times when the upper trade winds are most apt to increase with height are when the Azores High is farther north than normal for the season, or when a warm High is over the western North Atlantic.

Comparison between winds aloft over Puerto Rico in connection with a migratory cold High and a semipermanent High is shown in figures 8 and 9. The time cross section for December 22–25, 1957 (fig. 8), corresponds to a period when a migratory cold High moved off the continent and passed eastward north of Puerto Rico. On the time cross section the winds aloft decrease with height above the gradient level. With minor exceptions, therefore, the winds in the layer 4,000 to 6,000 feet are lighter than at lower levels. The base of the westerlies varies from 9,000 to 23,000 feet with a 2,000- to 3,000-foot transitional zone of weak winds between the easterlies and westerlies. The synoptic situation during this period is illustrated by the 1200 GMT surface map and the 1500 GMT 500-mb. chart for December 23, 1957 (fig. 6).

Figure 9 is a time cross section for January 28 to February 4, 1957. During this period a semipermanent High intensified in the western North Atlantic north of Puerto Rico. In figure 9 the winds aloft increase with height above the gradient level and the winds in the 4,000- to 6,000-foot zone are as strong or stronger than those at lower levels. The base of the westerlies is above 23,000 feet. The surface map and 500-mb. charts shown in figure 7 illustrate the position and intensity of the anticyclone causing these strong winds.

From the comparison between the two time cross sections it is apparent that the upper wind parameter will work best with semipermanent Highs since they are likely to cause strong winds aloft before strong winds are felt at the surface. To test the upper wind parameter with $\Delta p=8$, it was necessary to divide the data into

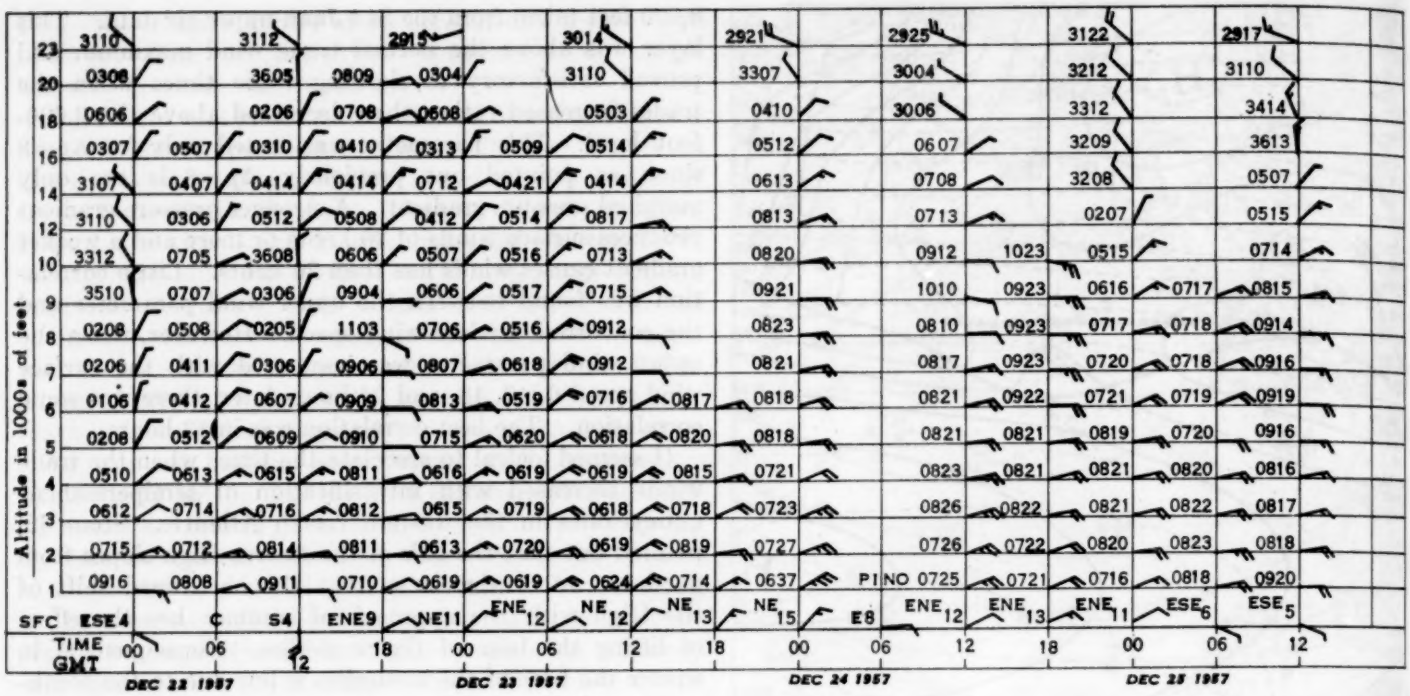


FIGURE 8.—Time cross section of winds at San Juan, P. R., from 0000 GMT, December 22, through 1200 GMT, December 25, 1957. Full barb on wind shaft equals 10 kt.; half barb equals 5 kt. Numbers to left of each wind are exact velocities with first two digits representing direction in tens of degrees and last two digits representing speed in knots. (See fig. 6.)

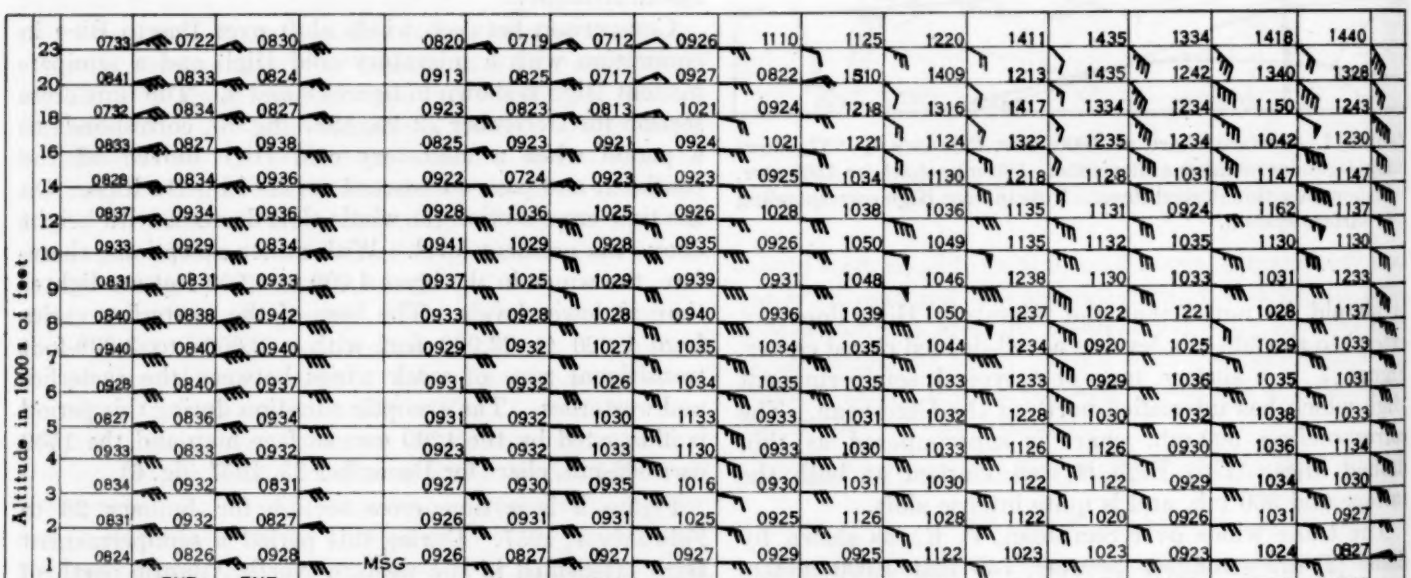


FIGURE 9.—Time cross section of winds at San Juan from 0300 GMT, January 28, through 1500 GMT, February 4, 1957. (See fig.7.)

migratory and nonmigratory cases. All occasions with $\Delta p=8$ were listed with their corresponding upper and surface winds; then the surface map for each occasion was inspected and cataloged as either migratory or nonmigratory. If an anticyclone was cold and did not extend as a well-defined closed center to 500 mb. and if its track showed a movement off the continent, it was classified as a migratory High; if an anticyclone was warm and extended as a well-defined center to 500 mb. and had not recently moved off the continent, it was classified as nonmigratory.

The winter of 1956–57 was used for development purposes. Using only data for semipermanent Highs and $\Delta p=8$, the upper wind parameter (maximum wind speed

TABLE 6.—*Contingency table of results of objective forecast procedures for semipermanent Highs for initial data (December 1956; January, February, March, 1957)*

		Forecast		
		Winds ≥20 kt.	Winds <20 kt.	Total
Observed	Winds ≥20 kt.	18	2	20
	Winds <20 kt.	5	11	16
	Total	23	13	36

Percent correct: 81 Skill score: 0.59

TABLE 7.—*Contingency table of results of objective forecast procedures for semipermanent Highs for test data (December 1953, 1954, 1955; January, February, March, 1954, 1955, 1956)*

		Forecast		
		Winds ≥20 kt.	Winds <20 kt.	Total
Observed	Winds ≥20 kt.	13	4	17
	Winds <20 kt.	2	27	29
	Total	15	31	46

Percent correct: 87 Skill score: 0.71

between 4,000 and 6,000 feet) was plotted against surface wind speed 12 hours later. It has already been shown that there was no significant correlation between the upper wind parameter and the current surface wind for $\Delta p=8$. Inspection of the plotted data showed best results with an upper wind of 25 knots. If the current upper wind parameter was above 25 knots, the surface wind was likely to be 20 knots or greater in 12 hours. Conversely, if the current upper wind parameter was 25 knots or less, the surface wind was likely to be less than 20 knots in 12 hours.

EVALUATION OF SYSTEM

Table 6 shows the results obtained from the development data. These data gave an accuracy of 81 percent with a skill score of 0.59.

It was not possible to compare the development data with the official forecasts since no records of Small Craft Warning forecasts were available. Instead the data were evaluated by analyzing data for the winters of 1953–54, 1954–55, and 1955–56 on a scatter diagram in the same manner as the development data. Table 7 based on this 3-year winter period shows an accuracy of 87 percent with a skill score of 0.71. As both the development data and check data are in good agreement and together cover a period of four winters, the upper wind and $\Delta p=8$ parameters may be considered useful forecast tools to predict strong surface winds associated with semipermanent Highs.

So far this upper wind method considered only semipermanent Highs because they appeared most likely to give significant results. To check the validity of using it for both migratory and semipermanent Highs, the same forecast method was applied only to migratory Highs for the 12-month period of the check data. The results are shown in table 8. This contingency table gave an accuracy of 66 percent with a skill score of 0.30 for migratory Highs. The difference in accuracy between the method applied to semipermanent Highs and to migratory Highs is enough to justify use of the upper wind parameter solely with semipermanent Highs. There were no other parameters investigated that showed as much forecast value as the upper wind and none in combination with the upper wind gave any forecast improvement.

TABLE 8.—*Contingency table of results of objective forecast procedures for semipermanent Highs applied to migratory Highs for test data (December 1953, 1954, 1955; January, February, March, 1954, 1955, 1956)*

		Forecast		
		Winds ≥20 kt.	Winds <20 kt.	Total
Observed	Winds ≥20 kt.	10	17	27
	Winds <20 kt.	2	27	29
	Total	12	44	56

Percent correct: 66 Skill score: 0.30

7. SUMMARY

The problem of forecasting strong winds over the coastal waters of the Dominican Republic, Puerto Rico, the Virgin Islands, and northern Leeward Islands during the winter was treated by dealing individually with the pressure gradient required to produce winds of 20 knots or greater and then with the synoptic conditions most likely to produce that gradient. When the pressure difference between 15° N. and 25° N. reaches or exceeds 9 mb. ($\Delta p \geq 9$), the winds should be 20 knots or greater. Combined forecast rules for predicting the onset of strong winds are as follows:

1. *Migratory Highs:* If a High moves across the western boundary (fig. 4) into the east coast area and its central pressure is—

   a. Above the critical value, 20-knot winds or greater should be expected in 24 hours.
   b. Below the critical value, no strong winds should be expected.
   c. At the critical value: (1) wait 12 hours; (2) check whether High is increasing or decreasing in intensity; (3) if central pressure goes above critical value 20-knot winds or greater should be expected in 12 hours; (4) if it goes below or remains at the critical value no strong winds should be expected, but the pressure gradient should be watched.

2. *Semipermanent Highs:* If a High develops or intensifies over the western North Atlantic:

   a. Watch until the pressure difference between 15° N. and 25° N. over Puerto Rico reaches 8 mb. ($\Delta p=8$).
   b. When the maximum wind speed in the layer

between 4,000 and 6,000 feet over San Juan exceeds 25 knots, forecast surface winds of 20 knots or greater in 12 hours.

Use of these forecast steps makes it possible to forecast the onset of strong winds over the coastal waters of the Dominican Republic, Puerto Rico, Virgin Islands, and northern Leeward Islands 12 to 24 hours in advance depending upon the synoptic situation responsible for the winds. The forecast systems for migratory and semipermanent Highs both proved over 80 percent accurate in predicting strong winds 12 or more hours in advance. Observing and forecasting the trend in the pressure gradient over Puerto Rico, intensification or weakening of a High, or exceptional speed or direction of motion of a High might eliminate many of the "misses." A few minor causes of strong winds were not treated because there were too few cases even in the 4 to 6 years used in this investigation.

This study does not represent a complete answer to the problems of forecasting strong winds over Puerto Rico and adjacent areas. There are other possible approaches that have not been explored, but many of them might be less objective and more complicated than the present system. It is hoped that this study will prove as useful as the results would seem to indicate. Even though an objective system often works better for its originators than for subsequent users, the reason may lie in familiarity with the methods employed. Once the forecaster becomes acquainted with the system and uses it as described, the results should prove compatible with the accuracy and skill indicated both by the basic and test periods.

ACKNOWLEDGMENTS

The authors acknowledge the helpful advice and encouragement of Mr. Ralph L. Higgs, meteorologist in charge, and the valuable suggestions and help received from Mr. José A. Colón, research forecaster at San Juan, P. R. The authors are indebted to the members of the San Juan forecast staff, and particularly Mr. Walter B. Davis, for their helpful comments, and to Mr. Ruben Perez for typing the manuscript.

REFERENCES

1. R. W. James, "The Latitude Dependence of Intensity in Cyclones and Anticyclones," *Journal of Meteorology*, vol. 9, No. 4, Aug. 1952, pp. 243–251.
2. Robert G. Stone, "On the Mean Circulation of the Atmosphere Over the Caribbean," *The Bulletin of the American Meteorological Society*, vol. 23, No. 1, Jan. 1942, pp. 4–16.
3. H. Riehl, T. C. Yeh, J. S. Malkus, and N. E. La Seur, "The North-east Trade of the Pacific Ocean," *Quarterly Journal of the Royal Meteorological Society*, vol. 77, No. 334, Oct. 1951, pp. 598–626.

HAIL DETERMINATION BY RADAR ANALYSIS[1]

BILLIE J. COOK

Radar Analysis and Development Unit (RADU), District Meteorological Office, U. S. Weather Bureau, Kansas City, Mo.

[Manuscript received February 6, 1957; revised September 4, 1958]

ABSTRACT

Radar reports from 17 radar stations are correlated with hail reports for the 4-month period April through July 1956. The relationship between radar detection of precipitation at long ranges and the occurrence of hail is studied. Fifty percent of all echoes reported at ranges of 135 n. mi. or greater are found to have contained hail. Results of an operational test of the method of analysis are given. Sixty-seven percent of all cases of ¾-inch or larger hail reported in the test area are found to have been identified by the term "Hail Indicated" in hourly radar summaries by the Radar Analysis and Development Unit at the time the hail was occurring.

1. INTRODUCTION

Use of the Weather Bureau Search Radar has suggested that echoes observed at long range frequently contain hail. This paper reports (1) results of a comparison of echoes observed at long range and reported occurrences of hail, and (2) results of preliminary operational tests of the suggested relationship by the Weather Bureau's Radar Analysis and Development Unit (RADU) in Kansas City, Mo.

Many factors must be considered when computing the power received at the radar antenna. Since Ligda [1] discusses these factors quite thoroughly they need not be discussed in detail here. Briefly, the return power is directly proportional to the sixth power of the radius of the precipitation particle and inversely proportional to the square of the distance to the target. It seems logical to assume that hailstorms, particularly those producing large hail, should be detected at long ranges since hailstones usually are much larger than the largest raindrops (about 5-mm. diameter). For example, a wet hailstone of 1-inch diameter gives approximately 3,400 times as much power return as a 5-mm. raindrop, all other factors assumed equal. Also, thunderstorms associated with hail are generally of greater vertical and horizontal extent than those associated with rain showers and would be more likely to intersect the radar beam at the long ranges.

The radars that provided the data for this study were WSR–1 and –3 (formerly APS–2) with a power output of approximately 60 kw. Although the radars are basically the same design and power, each had to be considered separately for verification purposes because of the differences in the local installation.

2. HAIL DATA

The hail reports used were taken principally from crop damage hail claims reported by over 100 insurance companies. Hail reports from *Climatological Data, National Summary*, and from hourly teletypewriter weather reports were also used. About 95 percent of the hail reports were taken from the 60,000 hail claims. Even with this many reports, it appears that only a small portion of the actual hail was reported. Figure 1 shows the total crop hail claims per degree latitude and longitude for the period April through July 1956. The shaded area of figure 1 is the test area and will be further discussed in the next section. The great majority of the hail claims were from areas where wheat or corn is the principal crop. Few, if any, claims were reported in wheat areas prior to the ripening of the wheat or after the wheat was gathered. Almost no hail reports were received from areas which are principally pasture or forest. The hail reports were plotted for each day with times when known. In most instances the exact times of hail occurrence could not be determined, but routine radar analysis by RADU indicated that in most instances thunderstorm activity occurred only once at the location of a hail report on a given day.

3. DATA ANALYSIS

Since the study was concerned with radar observations at long range, a range of 120 n. mi. was arbitrarily selected as the minimum. Thus the area between 120 n. mi. and the maximum range (160 to 210 n. mi. depending on the installation) was the area correlated with the hail reports. This area is referred to as the station sampling area in this paper. Seventeen stations were selected for verification on the basis that at least half of the station sampling area was in the area covered by hail claims. The shaded area of figure 1 is a composite of the 17 station sampling areas. Almost all of the Texas and Oklahoma area is covered by radar with ranges greater than 120 n. mi., while farther north the overlapping is less complete.

The original radar weather observations of the 17 stations were scanned and all echoes at ranges of 120 n. mi. or more were compared with the plotted hail data. These 4,759 echoes were not necessarily the strongest echoes, since the instructions were for the observer to report perimeter points of areas and as many points as necessary

[1] Some of the results of this study were given in a preliminary report entitled "Determination of Hail by Weather Bureau Search Radar" that was presented by the author at the Sixth Weather Radar Conference, Cambridge, Mass., March 1957.

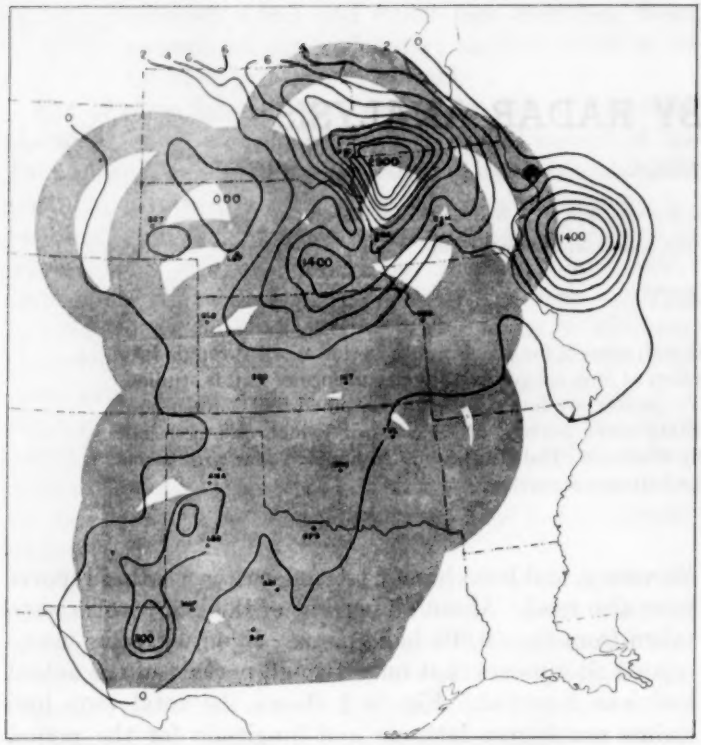


FIGURE 1.—Total hail claims per degree latitude-longitude for the period April through July 1956, with area of radar coverage shaded.

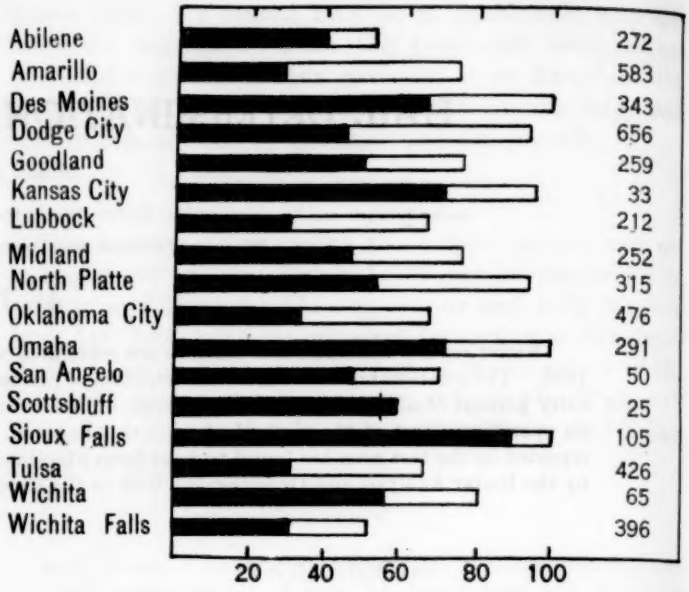


FIGURE 2.—Complete bar (solid+open) is the percentage of the station sampling area which fell within the area of hail claims. Solid part of bar is the percentage of the total echoes (shown by column of numbers on the right) that were verified as containing hail in the test period.

to define a line. If the echo was within 20 n. mi. of a hail report and within 1 hour of a known time of hail (either exact time or approximate time obtained from thunderstorm information), verification was considered positive. A single storm could be reported by more than one radar and for more than 1 hour, thus causing the storm to be verified several times. By the same token, some storms which could not be verified as producing hail were also verified negatively several times.

The radar stations had to be considered separately for verification purposes. For example, one radar detected 656 echoes during the test period while another detected only 25 in the same period. This might be a function of the weather to some extent, but is primarily due to the differences in the local installation and terrain. Furthermore, only a portion of the station sampling area fell in the area of hail claims. The complete bar (solid plus open) in figure 2 shows the percentage of the station sampling area that was within the area of hail claims. Very few hail reports were received outside the hail claim area, although it is possible that as much hail actually fell outside the area as within the area. Since all echoes in the station sampling area were considered in the verification, the verification percentages given by the solid bar in figure 2 should be considered a minimum verification, and of course, more complete hail reports would tend to increase the percentages over those given here. For example, Des Moines, Omaha, and Sioux Falls station sampling areas were completely within the area where hail claims were received and 65, 73, and 88 percent, respectively, of all their echoes were associated with hail; but those stations with only a portion of the station sampling area in the area covered by hail claims had poorer verifications.

Verification varied greatly from month to month due to the fluctuation in the area of hail reports. The U. S. Department of Agriculture *Grain Market Review* shows that in April few crops were at a stage where hail would damage them. Wheat had not begun to head and the Corn Belt was not planted, so relatively few hail claims were filed (fig. 3A). In May, wheat and other small grains were ripening in Texas and Oklahoma and corn was coming up in Iowa and Nebraska (fig. 3B). In June, wheat harvesting was well underway as far north as central Kansas (fig. 3C). In July, the small grains were mostly harvested in Texas and Oklahoma, but were still in the fields and subject to hail damage in Kansas and northward (fig. 3D). Superimposed upon this northward shift of crop damage is the climatological shift of severe weather which is normal during this season.

The dashed lines in figure 3 show that the percent of echoes verified follows the area of hail claims quite closely and a more complete hail report would tend to increase the total verification figures considerably. An interesting note is that almost all radar stations verified hail in over 50 percent of all echoes detected in the station sampling area during one month of the four.

Figure 4 shows that the percentage of verification increased in proportion to range. This of course, is an average for all 17 stations; individual stations might vary considerably from this average, particularly in the shorter ranges. However, the increase in verification from 56 percent at 150 n. mi. to 82 percent at 200 n. mi. suggests

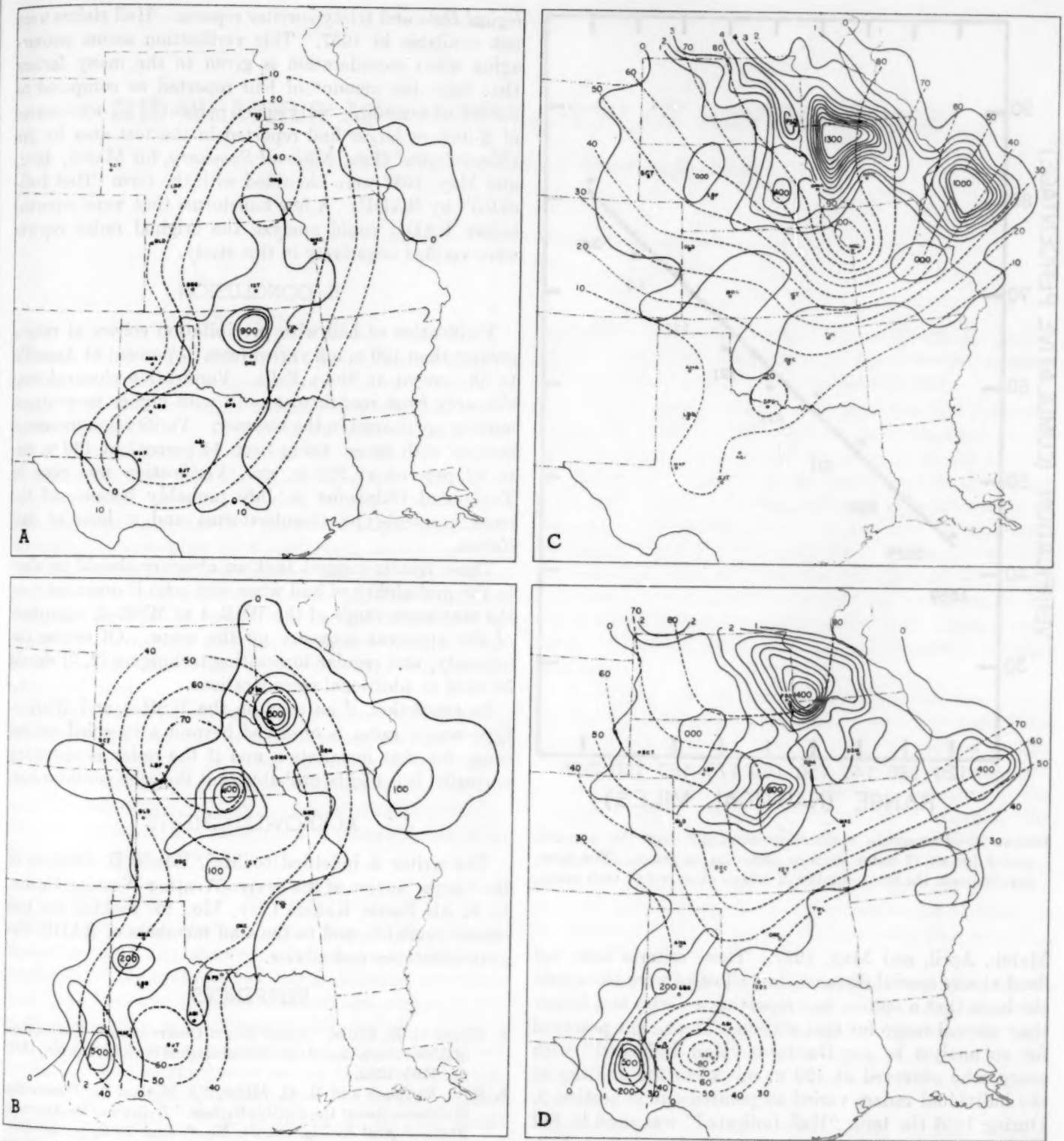


FIGURE 3.—Total hail claims per degree latitude-longitude and radar verification (percent) for (A) April 1956, (B) May 1956, (C) June 1956, and (D) July 1956.

that hail often accompanies storms detected at these ranges. The number below the curve is the total number of echoes at that range for the test period. The sharp drop in the total number of echoes between 180 and 190 n. mi. is explained by the 180-n. mi. maximum range of many of the radars.

4. OPERATIONAL TEST

In a preliminary operational test of the relationship shown by the above results, RADU's hourly radar summary included the term "Hail Indicated" with those echoes meeting certain range criteria during 1956, and

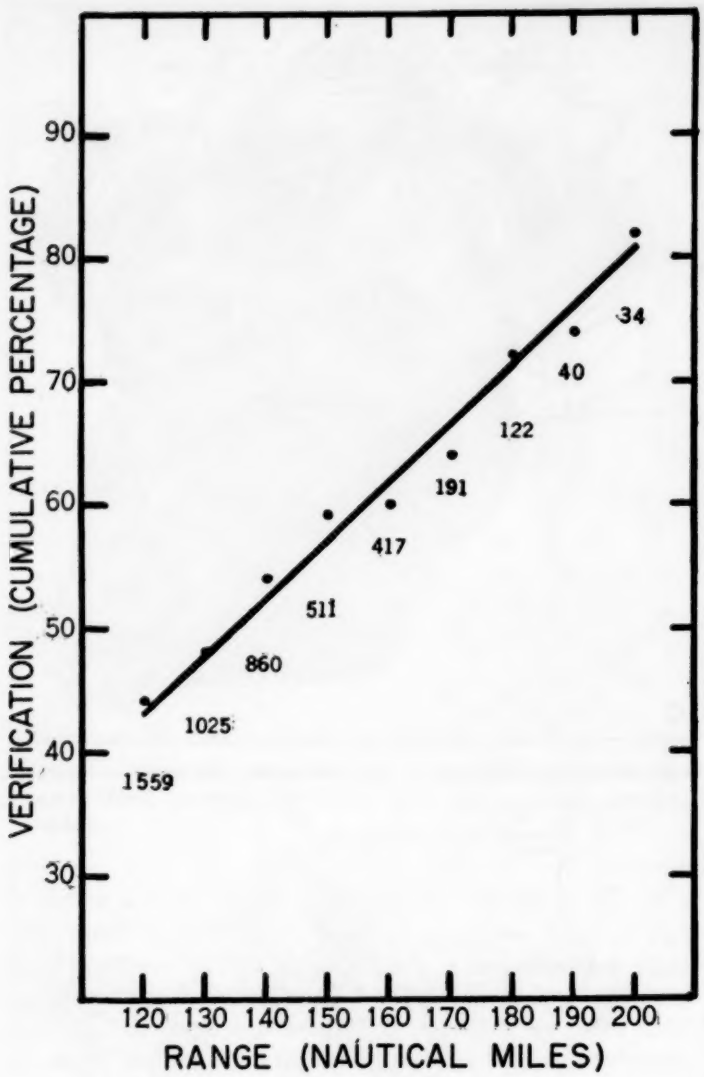


FIGURE 4.—Percentage verification averaged over the 4-month period for all 17 radar stations according to range. The numbers indicate the total number of echoes observed at each range.

March, April, and May, 1957. These criteria were not fixed at any special distance, but all cases were chosen on the basis that a station was reporting an echo at a longer than normal range for that station. It was not practical for an analyst to use the term "Hail Indicated" with every echo observed at 120 n. mi. when the abilities of the individual radars varied as pointed out in section 3. During 1956 the term "Hail Indicated" was used in 182 cases; 56 percent of these were verified as having hail. During March and April 1957 the term was applied to 347 echoes and 35 percent were verified from *Climatological Data* and teletypewriter reports. Hail claims were not available in 1957. This verification seems encouraging when consideration is given to the many factors that limit the amount of hail reported as compared to the actual amount. Sixty-seven percent of all occurrences of ¾-inch or larger hail reported in the test area by the *Climatological Data, National Summary*, for March, April, and May, 1957 were identified with the term "Hail Indicated" by RADU. A few hailstorms that were reported before RADU could analyze the original radar reports were verified negatively in this study.

5. CONCLUSION

Verification of hail with precipitation echoes at ranges greater than 120 n. mi. varied from 27 percent at Amarillo to 88 percent at Sioux Falls. Verification changed considerably from month to month with higher percentages moving northward in the summer. Verification increased sharply with range, rising from 44 percent at 120 n. mi. to 82 percent at 200 n. mi. Verification was poor in Texas and Oklahoma in July probably because of the more tropical-type thunderstorms and a lack of hail claims.

These results suggest that an observer should be alert to the probability of hail when any echo is observed near the maximum range of the WSR–1 or WSR–3, regardless of the apparent intensity on the scope. Of course the intensity, and regular forecasting techniques [2, 3] should be used as additional considerations.

In conclusion, if an echo on the WSR–1 and WSR–3-type search radar is observed beyond a specified critical range for that installation and if the radar is operating normally, it is highly probable that the echo contains hail.

ACKNOWLEDGMENTS

The writer is indebted to Maj. Edwin B. Dickson of the Sferics Section of the Severe Weather Warning Center, U. S. Air Force, Kansas City, Mo., for making the hail claims available, and to the staff members of RADU who gave assistance and advice.

REFERENCES

1. Myron G. H. Ligda, "Radar Storm Observation," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 1265–1282.
2. E. J. Fawbush and R. C. Miller, "A Method for Forecasting Hailstone Size at the Earth's Surface," *Bulletin of the American Meteorological Society*, vol. 34, No. 6, June 1953, pp. 235–244.
3. D. S. Foster and F. C. Bates, "A Hail Size Forecasting Technique," *Bulletin of the American Meteorological Society*, vol. 37, No. 4, Apr. 1956, pp. 135–141.

THE WEATHER AND CIRCULATION OF NOVEMBER 1958[1]

A Mid-Month Reversal of Weather Regimes

ERNEST PAROCZAY

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

It was found by Namias [7] that for the period 1942–50 the month-to-month persistence of temperature, precipitation, and 700-mb. height anomaly in the United States was less from October to November than for any other pair of adjacent months. Recent Novembers [4, 10] have confirmed the fact that abrupt changes often take place between those months. In his study, Namias also indicated that intramonthly fluctuations are common in November. November 1958 conformed, as a reversal in both temperature and precipitation was observed between the first and second halves of the month, with associated changes in the 700-mb. height field and its jet stream. As a consequence of these changes, the eastern portion of the Nation became warmer and wetter, while the West turned colder and drier.

Because of the contrasting regimes that occurred during the month, it is difficult to discern in the monthly mean circulation underlying physical explanations of temperature and (especially) precipitation anomalies. For this reason the monthly circulation was divided into two 15-day periods to facilitate the association of observed anomalies with the changing circulation.

2. CIRCULATION OF NOVEMBER 1–15, 1958

The 15-day mean 700-mb. chart for the first half of November (fig. 1A) showed a mean trough of small amplitude off the east coast of North America, extending from Cape Hatteras to Newfoundland and thence northward, terminating in northwestern Greenland. A somewhat similar position was occupied by a mean trough last month [1]. The blocking over central Canada, which was so prevalent during September [2] and October, relaxed during this period. This is indicated by the small amplitude of the major ridge over the western portion of North America. The associated mean trough downstream also flattened, resulting in 700-mb. heights averaging below normal over almost all of North America, with centers of maximum departure from normal over southwestern Canada, eastern Alaska, and Nova Scotia. Over the United States small height anomalies and rather strong zonal flow were observed during the first half of the month. In this period the jet stream at 700 mb. was generally oriented east-west, except in the middle portion of the country where a southward dip of the jet occurred before it exited over North Carolina (fig. 2A).

It is characteristic of high-index type flow that numerous fast-moving minor perturbations may manifest themselves as mean minor troughs, especially to the leeward of mountains. Such a trough developed in the strong zonal flow over the Central States. It is interesting to note that this trough formed at the base of maximum curvature of the jet stream (fig. 2A). While this position is somewhat removed from the influence of the Rocky Mountains, it is located in a position of maximum 30-day mean trough frequency for November [6]. Thus, a composite of factors resulted in the minor trough through that area.

The strong ridge in the mid-Pacific, which was clearly marked by a large area of positive anomaly during the month of October, was replaced by a well-defined trough. This split the central Pacific ridge into two cells; one located in the west-central Pacific and the other in the eastern Pacific. Associated with these changes, the trough of October in southwestern United States was propagated eastward. The positions of the troughs and ridges in the Pacific over the middle latitudes and over most of North America closely corresponded to those in September [2], also a month of high index flow over the United States.

The eastern Atlantic ridge intensified from October to November and resulted in an especially strong departure from normal (+420 feet) off the coast of Europe (fig. 1A). The amplification continued downstream, marked by the intensification of the trough from central Europe southward to north-central Africa.

In response to this amplification, intense ridging occurred over eastern Europe just west of the Ural Mountains, culminating in a departure from normal of +540 feet over east-central Russia where 700-mb. heights had been a little below normal in October. Meridional flow was observed over the European continent, in contrast to the zonal flow over North America. The pattern over most of Asia was similar to that over the Western Hemisphere, with flat wave systems and a relatively smooth anomaly pattern.

The Low centered over the North Pole in September

[1] See Charts I-XVII following p. 456 for analyzed climatological data for the month.

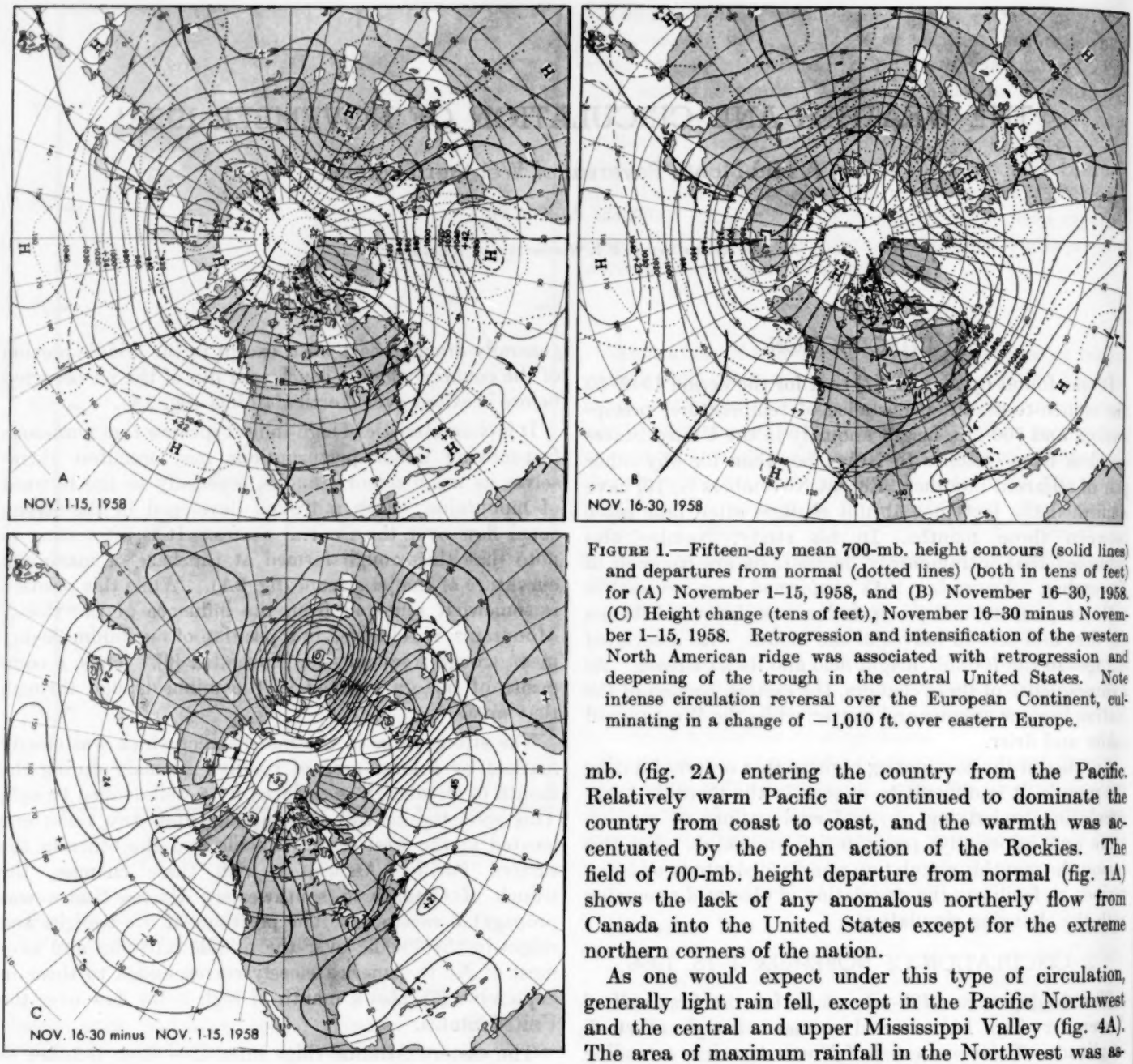


FIGURE 1.—Fifteen-day mean 700-mb. height contours (solid lines) and departures from normal (dotted lines) (both in tens of feet) for (A) November 1–15, 1958, and (B) November 16–30, 1958. (C) Height change (tens of feet), November 16–30 minus November 1–15, 1958. Retrogression and intensification of the western North American ridge was associated with retrogression and deepening of the trough in the central United States. Note intense circulation reversal over the European Continent, culminating in a change of −1,010 ft. over eastern Europe.

reached its maximum intensity in October, with an anomaly of −420 feet. In November this large negative anomaly split, with a portion swinging into Alaska and another section into northern Greenland, while a small positive anomaly developed in extreme north-central Canada.

3. TEMPERATURE AND PRECIPITATION ANOMALIES OF NOVEMBER 1–15

The temperature anomaly (fig. 3A) clearly illustrates the abnormally warm nature of the first half of November. The largest departures from normal occurred over the central portion of the country, with extremes of as much as +10° F. in Kansas and western Missouri. The warmth was the result of fast westerlies in high index circulation, as indicated by the strong jet stream at 700 mb. (fig. 2A) entering the country from the Pacific. Relatively warm Pacific air continued to dominate the country from coast to coast, and the warmth was accentuated by the foehn action of the Rockies. The field of 700-mb. height departure from normal (fig. 1A) shows the lack of any anomalous northerly flow from Canada into the United States except for the extreme northern corners of the nation.

As one would expect under this type of circulation, generally light rain fell, except in the Pacific Northwest and the central and upper Mississippi Valley (fig. 4A). The area of maximum rainfall in the Northwest was associated with the jet at 700 mb. (fig 2A) carrying moist maritime airmasses against the mountainous terrain. Notice the drying effect of the Rocky Mountain range as the jet moved southeastward from Montana to northeastern Nebraska and Missouri. Moderate to heavy rainfall in the Mississippi Valley was related to the minor 700-mb. trough there, as small perturbations produced rainfall, aided by a flow of moist southerly winds.

4. MID-NOVEMBER CIRCULATION TRANSITION

The 15-day mean 700-mb. chart for November 16–30, 1958 (fig. 1B), shows the Alaskan Low replaced by a blocking High, with a maximum anomaly of +210 ft. (fig. 1B), situated between Alaska and the North Pole. This anticyclogenesis affected the general circulation over both the Pacific Ocean and the North American continent.

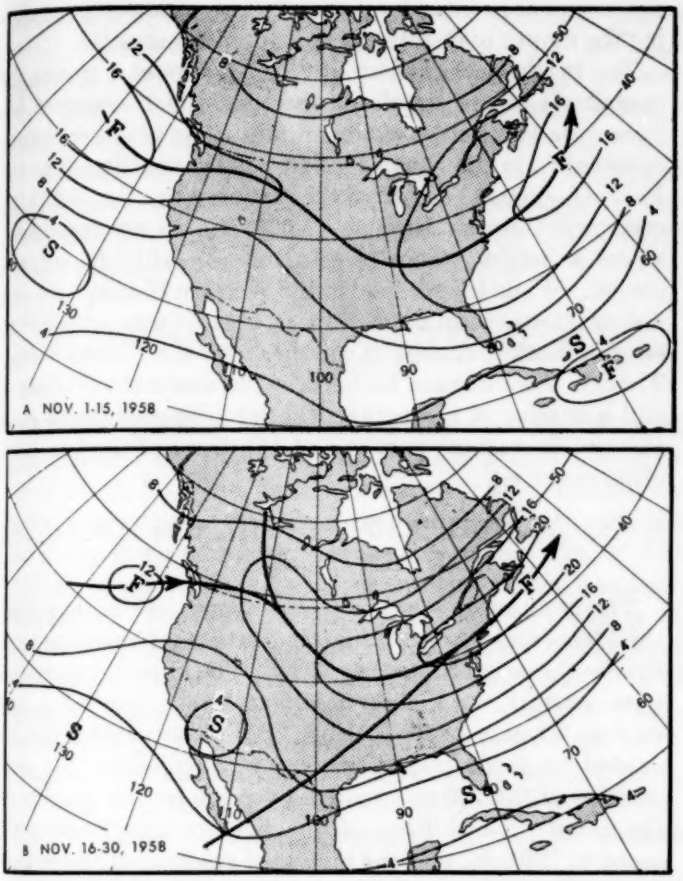


FIGURE 2.—Fifteen-day mean 700-mb. isotachs (meters per second) with position of the primary jet axes given by solid arrows for (A) November 1–15, 1958, and (B) November 16–30, 1958. The development of a northerly jet out of central Canada and a southwest jet from Texas, plus a slight northward shift from the first to the second halves of the month, were associated with cooling and drying in the West and warming and more precipitation in the East.

The west coast ridge retrograded and built over the northern two-thirds of the area, while the southern portion became weaker. Downstream, the minor trough that had been located in the Central States during the first half of the month (fig. 1A) retrograded and joined with the southwest trough to establish a major 700-mb. trough extending from the western Lakes Region southwestward through the southern Rocky Mountain States, terminating off Lower California (fig. 1B). As this trough connection was made, the east coast trough from Cape Hatteras to Labrador disappeared and heights rose over the southeastern United States. The remainder of the trough retrograded slightly as a result of the wave configuration and vorticity flux from the blocking High. The associated 700-mb. low center moved from western Greenland southwestward to a position just west of Baffin Island (fig. 1B).

With the Polar Low over the Alaskan region replaced by a ridge and blocking system, the northern end of the full-latitude trough in the central Pacific (fig. 1A) disappeared, while the southern end deepened considerably as it moved from near the central Pacific to some 300 miles east of the

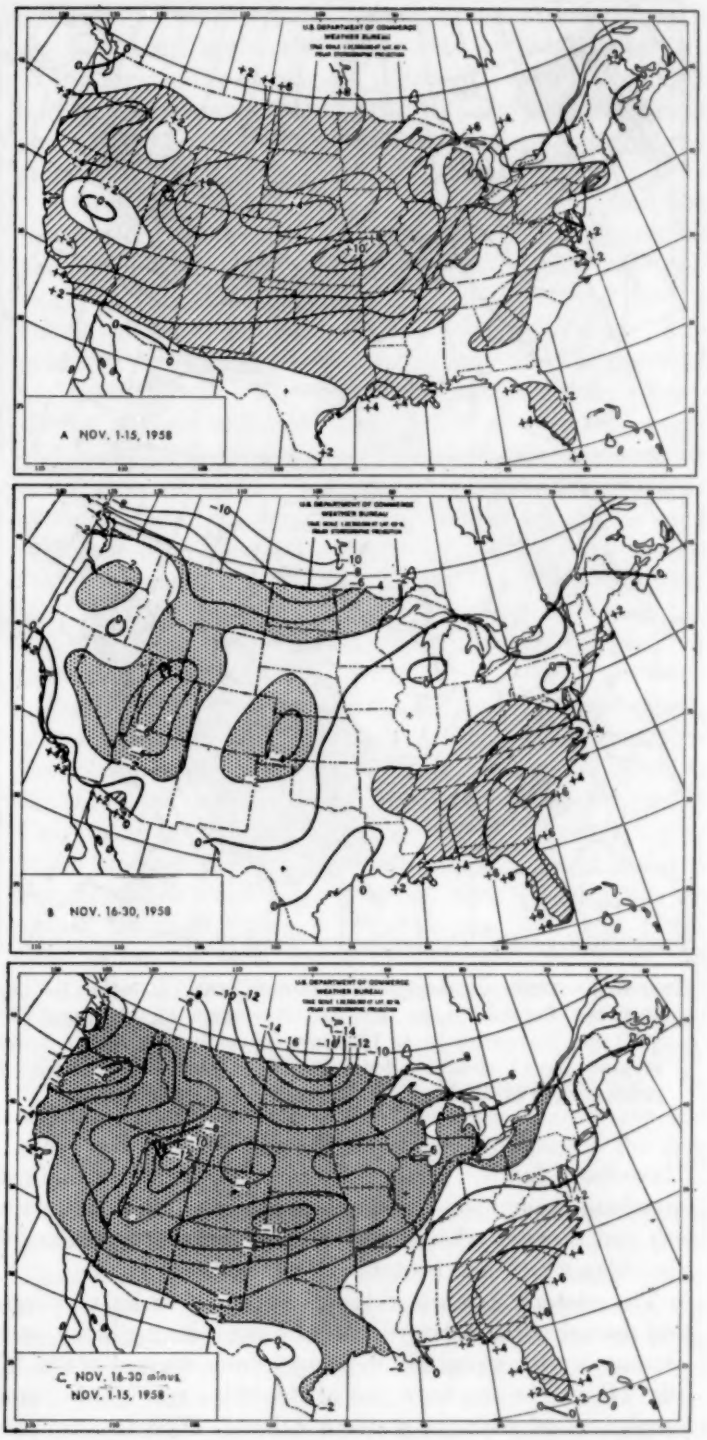


FIGURE 3.—Departure of average temperature from normal (° F.) for (A) November 1–15, 1958, and (B) November 16–30, 1958. (C) Temperature change (° F.), November 16–30 minus November 1–15, 1958. Anomalies greater than ±2° F. are shaded. The sharp reversal from a warm regime over most of the country to cold in the West and warm in the East was one of the outstanding features of the month. The intensity of the change is brought into sharp focus by the chart of temperature change between the two halves of the month.

491985—59——2

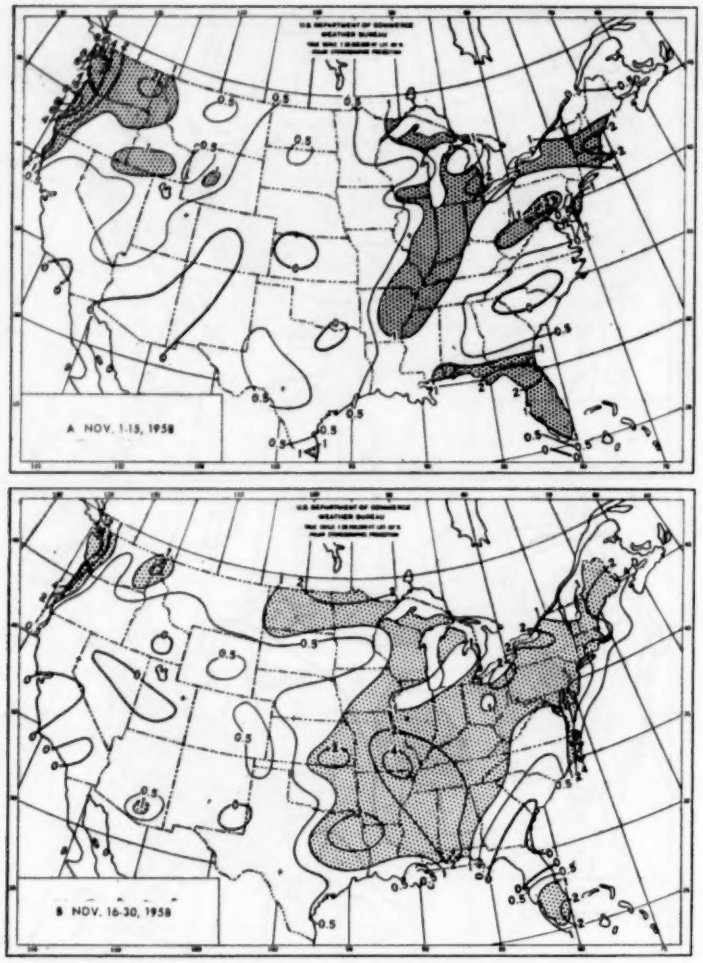


FIGURE 4.—Observed precipitation (approximate) in inches for (A) 1900 EST, October 31, to 1900 EST, November 15, 1958, and (B) 1900 EST, November 15, to 1900 EST, November 30, 1958. Areas greater than 1 inch are shaded. Drying in the West and increased precipitation in the East were characteristic of the month.

Hawaiian Islands. The Asiatic east coast trough remained quasi-stationary from Hokkaido southward, while its northern end sheared off and replaced the northern portion of the ridge which had been in the west-central Pacific.

The eastern Atlantic ridge disappeared as its northern end moved northeastward, establishing a strong block over Denmark with a positive departure from normal of 630 ft. (fig. 1B). The southern end of this ridge retrograded and amalgamated with the western Atlantic High to form one zonally oriented anticyclone extending across the Atlantic. Filling occurred in the Mediterranean trough, but it still remained well defined over the water. The trough that had been located east of the Caspian Sea (fig. 1A) during the first half of the month retrograded and deepened considerably (−570-ft. anomaly) and joined with the short trough over extreme north-central Asia. This junction formed a strong full-latitude trough from the Caspian Sea north-northeastward to northern Asia (fig. 1B). This flow pattern contrasted with that for the earlier part of the month, particularly in the complete reversal of the anomaly height field in the Ural Mountain area. It is interesting to observe that a similar circulation reversal occurred during the month of October in the European area [1].

The height change chart (fig. 1C) shows at a glance the magnitude of the circulation reversal which occurred between the two halves of the month. The greatest change occurred from the North Pole (+330 ft.) southward to the Pacific (−360 ft.) and from the eastern Atlantic (−450 ft.) eastward through Europe (+620 ft.) to western Asia, where a height change of as much as −1010 ft. was observed. While the reversal in the Western Hemisphere was not as intense as in the European area, it was sufficient to effect a marked change in weather over the United States. Though the ultimate cause of such weather reversals is still a matter of conjecture, the interdependence of such changes in various portions of the hemisphere has been often observed.

5. TEMPERATURE AND PRECIPITATION ANOMALIES OF NOVEMBER 16–30

The greatest changes in temperature were cooling over the Plains and Rocky Mountain States and warming over the Southeastern States (fig. 3C). The largest departures from normal were observed over Utah (−6° F.) and western Florida (+8° F.) (fig. 3B). The pattern can be related to three major changes in circulation: the new position of the 700-mb. trough over the central portion of the country, a shifting of the field of maximum wind speed at 700 mb., and the increased gradient of anomalous flow. The position of the trough from the western Great Lakes to Arizona aided in advecting warm air into the Southeast. Notice the axis of 700-mb. wind speed maximum from Texas to southeastern New York (fig. 2B). This jet stream was completely lacking during the first half of the month (fig. 2A). It rapidly advected warm air into the Southeast where this warmth became firmly entrenched for the remainder of the month. The filling of the southern portion of the east coast trough, plus the resultant increase of heights (+50 to +140 ft.), also contributed to the warmth of the Southeast.

At the same time, intensification and retrogression of the ridge in western North America, combined with deepening of the 700-mb. trough over the central United States, brought about an influx of cold Canadian airmasses into the western half of the Nation (Chart IX). Note the development of an area of maximum wind at 700 mb. from west-central Canada into the United States (fig. 2B) and its absence earlier in the month (fig. 2A). It is of interest to observe the northerly anomalous flow (fig. 1B) in the area of cooling, compared with the west to southwest flow that was evident earlier (fig. 1A). Figure 3C shows that the greatest temperature changes occurred in Kansas (−11° F.), North Dakota (−15° F.), and southeastern Georgia (+6° F.). Figure 1C also reflects the invasion of colder air into the West with its increased northerly flow of Canadian air.

The precipitation pattern for the last half of the month was characterized by desiccation in the West and generally larger amounts (fig. 4B) in the East. The retrogression

and building of the ridge along the west coast, plus a slight northward shift of the 700-mb. "jet stream," induced a drier 15-day period in the Pacific Northwest and Rocky Mountain States. Pacific coastal stations that had previously reported rainfall amounts of 8 to 9 inches had only 4 to 5 inches during the last 15 days of November, while portions of the Mississippi Valley doubled their precipitation amounts under the influence of increasing southerly flow of moist Gulf air.

6. CHRONOLOGY OF PRINCIPAL STORMS IN NOVEMBER

Violent weather characterized the first few days of November. On the 3d, a vigorous low pressure disturbance swept into the Pacific Northwest, accompanied by damaging winds. As the Low continued through the northern Rocky Mountain States, Northern Plains, and Middle West, it caused widespread wind damage and set records at numerous stations. The wind of 75 m. p. h. recorded at Lander, Wyo., on the 4th was the highest ever recorded there in November and came within 2 m. p. h. of their alltime high. At Olympia, Wash., southerly winds reached 60 m. p. h. with gusts of 76 m. p. h. which overshadowed their previous record of 55 m. p. h. set in December 1945. In the wake of the storm, cold air poured into the North-Central States, producing the coldest weather of the season there.

On November 9 another disturbance with attendant high winds affected the Pacific Northwest and, in succession, the northern Rockies and Great Plains. Exceptionally warm southerly winds accompanied this storm in the central Rockies, where new heat records were established. The Elko, Nev., airport temperature records were toppled on the 8th and 9th. The 74° F. observed on the latter day was the highest temperature ever recorded in November at this station. At Winnemucca, Nev., a new heat record for the day and for so late in the season was established on the 9th when 75° F. was recorded. Copious amounts of precipitation occurred with the low center. The disturbance created near blizzard conditions through mountain passes of Colorado and Montana.

To the south and east of this frontal system, the exceptionally warm southerly flow gave 80° weather on the 10th to eastern Colorado, western Kansas, and the north central border of Nebraska, and warmed the Southeastern States. In the week ending November 17, record and near-record high temperatures spread through much of the central and eastern part of the country. Greatest departures, as much as +18° F., were observed from the south-central Plains northeastward to Illinois. The northward displacement of warmth was aided by a Low in the Rockies and by a strong High over the Southeastern States, creating abnormally strong southerly winds. Alltime heat records for so late in the season were established at numerous cities in Alabama, the Carolinas, Florida, Georgia, Indiana, Illinois, Kentucky, Michigan, Ohio, Pennsylvania, Tennessee, and West Virginia.

The rapid eastward motion of the two storms through the northern Rockies and Plains States was characteristic of the high index circulation observed during their existence. The strong jet stream (fig. 2A) and a weak ridge in the western United States (fig. 1A) effectively steered the storms rapidly through the Northern States.

By far the major feature of this month was the first intense, large snowstorm of the season. The storm center associated with the severe weather developed over Nevada on the 14th. By the 17th, it developed into a classic winter-type storm [8] over western Texas. The principal conditions necessary for such development of an intense storm were all available: an abundant supply of very cold air to the north, an inflow of unusually warm and moist air from the south, plus a favorable upper-air circulation pattern. This storm is discussed in great synoptic detail in an adjoining article by Saylor and Caporaso [9]. The storm deepened rapidly in the mean 700-mb. trough (fig. 1B) as it moved in a northerly direction through the Great Plains, generally following the 700-mb. trough before passing into extreme southwestern Ontario on the 18th.

Fourteen States were affected by this vigorous storm. The disturbance spread record-breaking snows into Arizona, New Mexico, the Great Plains, and as far north as Montana. The cold Arctic air poised over southwestern Canada swept into the Southwestern States, bringing bitter cold temperatures and new records for so early in the season in California, Arizona, and Nevada; for example, Flagstaff, Ariz., −13° F. on the 18th; Ely, Nev., −10° F. on the 16th; Santa Maria, Calif., 25° F. on the 17th. An interesting item is quoted from the *Local Climatological Data* for Tucson, Ariz. "Since 1895, snow has been recorded only once before in November [1919], and the total for that occurrence was only a trace. In addition, the 24-hour total of 6.4 inches of snow [on the 16th] was the greatest recorded for that period for any month since 1895."

Strong winds accompanied the storm and caused extensive drifting and blowing of snow. Many areas from Texas northward to the Canadian border reported extensive property damage. Many tornadoes occurred in the center of the Nation. Peak wind gusts of 104 m. p. h. were reported at Childress, Tex., as the cold air swept into that State. Winds clocked at 60 m. p. h. in Minneapolis, Minn., on the 17th broke their alltime record of 47 m. p. h. recorded back in 1913. The storm was climaxed with a loss of 33 lives as the freighter *Carl D. Bradley* broke up in a gale in northern Lake Michigan on November 18.

The month of November faded into the past with a snow and ice storm lasting from the 27th through the 30th. The low-pressure disturbance spread glaze and snow in a wide belt from the Central and Southern Plains to New England. The storm first developed over the central Rockies and moved into west Texas on the 28th where it filled. At the same time, a new low center developed over the western Gulf of Mexico and deepened as it

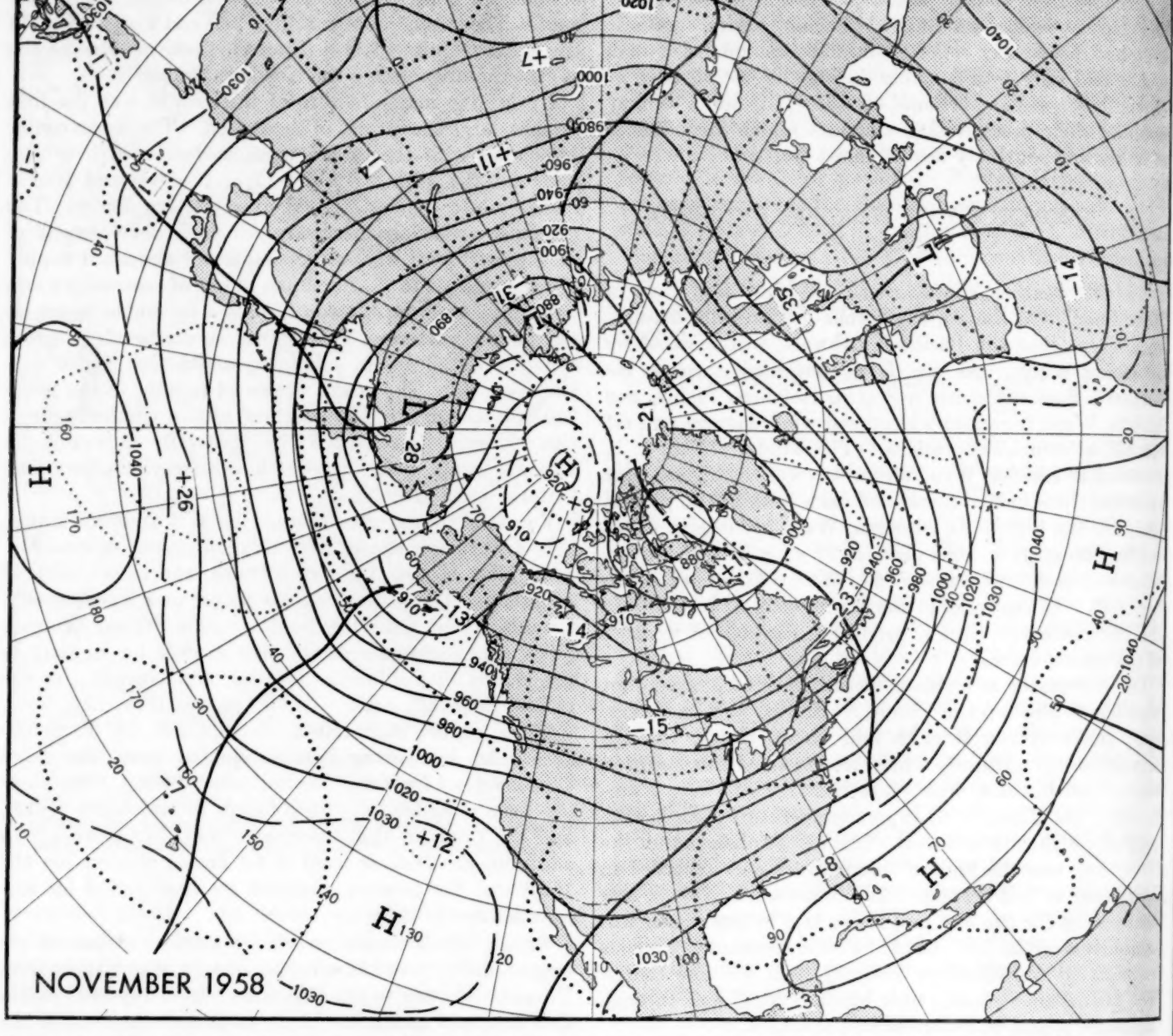


FIGURE 5.—Mean 700-mb. height contours (solid lines) and departures from normal (dotted lines) (both in tens of feet) for November 1958. Major circulation features over North America were trough-ridge systems of minor amplitude, characteristic of high-index circulation, with relatively small departures from normal over the United States. The intense polar Low of October filled and was replaced by a blocking High. The ridge over eastern Europe continued to build, resulting in a departure from normal of +350 ft.

rapidly moved northeastward, following the jet stream (fig. 2B) at 700 mb. to the central Appalachians, across New England, over the Gulf of St. Lawrence, and northward into the Labrador Sea on the 30th, where it subsequently filled and disappeared. As the storm swept northeastward, it was accompanied by gale force winds, especially over southeastern New England, where peak gusts of 60–70 m. p. h. caused property damage. The storm caused heavy snow north of its center, with accumulations up to nearly 3 feet in western New York State and up to a foot in northwestern Pennsylvania and northeastern Ohio. At Evansville, Ind., the 6.9 inches of snow exceeded any previous November daily total snowfall in 62 years. At Oklahoma City, 24-hour snowfall of 2.6 inches on November 27–28 was the greatest 24-hour amount in 69 years of record for the month of November. The storm caused widespread hazardous highway conditions during the Thanksgiving holiday season.

Intense cold accompanied by strong northerly winds blew across the Great Plains, Central States, and eastern portions of the country. New record low temperatures were established in parts of Ohio, western Pennsylvania,

and Indiana on the 29th and 30th. This November made its exodus with extremely cold air gripping most of the Nation from the Great Plains eastward.

7. MONTHLY SUMMARY OF CIRCULATION AND WEATHER ANOMALIES

Because of the changing regime, the mean monthly 700-mb. chart for November (fig. 5) did not display any outstanding features or large departures from normal. However, as one might expect, the monthly mean chart exhibited many of the major features present on the half-monthly mean charts (fig. 1). The North American east coast trough which was evident during the first half of the period was still observed on the monthly mean, in spite of the slight ridging that occurred during the latter part of the month over the Southeastern States. The trough in the central United States which intensified, retrograded, and combined with the southwest trough during the second half of the month, is also observed on the monthly mean. The full-latitude trough in the central Pacific, which was quite prominent during the early part of November, was destroyed at its northern end during the latter part of the month, and was therefore reflected as only a mid-latitude trough on the monthly mean.

The ridge remained along the coast of western North America with building heights toward the pole. This area reflected the greatest change between October and November as a rise of 460 ft. occurred north of Alaska (fig. 6) where the polar vortex was replaced by a blocking High. The resultant Ω-type circulation at high latitudes was associated with two other major changes. One occurred over Siberia with a fall of 340 ft. as lower heights replaced the weak ridge that existed in October. The second was a height change of −330 ft. (fig. 6) north of Hudson Bay as a Low developed over Baffin Bay in the eastern leg of the Ω-type block system. Other important changes took place in the central Pacific as the strong ridge of October, evidenced by a departure from normal of +360 ft. [1], gave way to trough conditions, resulting in a fall of 260 ft.

General ridging took place in Europe, evidenced by height rises of 310 ft. over central Europe and 260 ft. off Scotland. Even though a bimonthly change of large magnitude took place over most of the European continent, the block that developed over Denmark during the latter half of the month was reflected on the monthly mean by a height anomaly of +350 ft. (fig. 5). The central Eurasian trough, which only became well established during the second half of the period, was observed as sheared off from the low cell in extreme north-central Asia in almost the same fashion as in the first part of the month (figs. 1, 5).

Of interest is the fact that the zonal index, a measure of the net geostrophic west wind flow from 35° to 55° N. in the Western Hemisphere, was 1.0 m. p. s. faster than normal in November, making this the seventh consecutive month of above normal index. This extended period of fast westerlies was temporarily interrupted during the latter half of October but resumed in November.

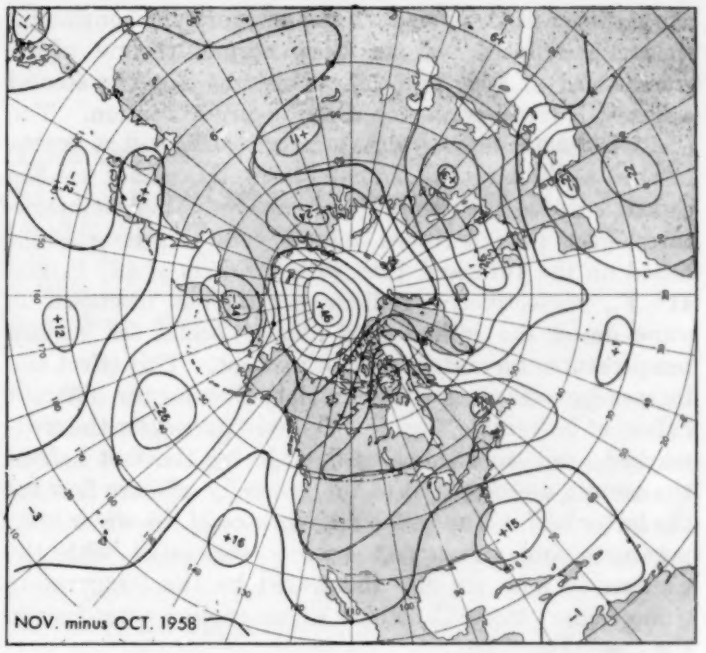


FIGURE 6.—Difference between the monthly mean 700-mb. height departures from normal of October and November 1958 (in tens of feet). The largest change occurred near the pole (+460 ft.), incident to the filling of the polar vortex and its replacement by a blocking High. Relaxation of blocking over Canada was reflected by a change of −330 ft. north of Hudson Bay.

Small temperature anomalies (Chart I–B) were observed over the United States, with almost the entire Nation averaging above normal. Positive temperature anomalies are typical of the high index circulation that existed during November. The anomalies were small, not only because of the temperature reversal that occurred during the month, but also due to rather weak, ill-defined anomalous flow associated with near normal heights over the United States. The small negative anomalies in the extreme northern Rocky Mountain States were associated with some weak northerly anomalous flow.

While the monthly averages lacked large extremes, many daily temperature records were broken in the western part of the country in the establishment of new highs during the first half of the month, followed by record lows during the latter part of the month. The development of a southwest jet during the latter part of the month advected warm air masses into the southern and eastern United States, where many longstanding heat records were toppled.

The abnormally warm weather which had persisted for the past several months in California [1, 2] abated somewhat in November as a result of an invasion of very cold Canadian air that occurred in connection with an intense storm in the Rocky Mountain and Great Plains States from November 14–16. In spite of the general cooling, Los Angeles International Airport continued to report much above normal temperatures [7], making November

the 21st consecutive month in this category and continuing the uninterrupted warmer than normal regime which commenced in May of 1956. This was also the second warmest November on record at the airport station. The city office continued to show similar warmth, but not as marked as the airport. In San Diego, November was the eighth consecutive month with above-normal temperatures, even though record low temperatures were established on the 16th and 17th with readings of 42° F. and 41° F., respectively. Ballenzweig [2] has discussed in some detail the influence of above normal sea surface temperatures for waters along the coast. This effect can be seen by examining the anomalous flow for the different halves of November (fig. 1). Note in particular the well-marked, onshore anomalous flow during the first half of the month, as compared to the generally offshore flow for the latter half. The lessening influence of the water temperatures and subsequent cooling associated with the changes in flow are also illustrated by the temperature change chart (fig. 3C), which shows cooling extending to the coastal stations.

Precipitation was relatively well distributed over most of the United States except for the southern Carolinas and central California, where less than one-half of the normal precipitation was observed, and the extreme northern Rocky Mountain and Plains States, where over twice the normal precipitation fell (Chart III–B). The precipitation pattern was the result of a scattering of storm tracks during the month (Chart X). The first part of the month was characterized by several east coast storms, followed by an absence of any such disturbances during the last half of the month. The Pacific Northwest and northern tier of States was an area of storminess accompanied by moderate to heavy rain as storms from the Pacific and Canada traveled through that area (Chart X). This was the wettest November ever recorded in Stampede Pass, Wash., and the second wettest November on record at Havre, Mont. During the latter part of the month the storm track shifted to the Plains States, Mississippi and Ohio Valleys, and the northeastern United States as a result of filling of the lower portion of the east coast trough in response to the retrogression and deepening of the central United States trough as it joined with the trough over the Southwest.

November may be summed up as a month of storminess, rapid changes in temperature, and early cold over the West and late warmth in the Southeast.

8. TROPICAL STORM ACTIVITY

No tropical storm activity was observed in the North Atlantic during the month, where on the average two storms are expected to develop every 5 years [3]. However, in the Pacific considerable tropical activity occurred; 5 storms were observed within the month, 3 of which developed during November. Activity was considerably above normal in this area for so late in the season [5]. Two of the three storms developed into typhoons, both of which recurved and became extratropical. The third tropical storm never attained typhoon proportions and did not move more than 6° of latitude from its birthplace during its life cycle. None of the tropical storms affected land areas.

REFERENCES

1. J. F. Andrews, "The Weather and Circulation of October 1958—A Month Characterized by a Pronounced Index Cycle," *Monthly Weather Review*, vol. 86, No. 10, Oct. 1958, pp. 408–415.
2. E. M. Ballenzweig, "The Weather and Circulation of September 1958," *Monthly Weather Review*, vol. 86, No. 9, Sept. 1958, pp. 359–367.
3. E. M. Ballenzweig, "Seasonal Variations in the Frequency of North Atlantic Tropical Cyclones Related to the General Circulation," *National Hurricane Research Project Report* No. 9, U. S. Weather Bureau, July 1957, 32 pp.
4. C. R. Dunn, "The Weather and Circulation of November 1956—Another October to November Circulation Reversal," *Monthly Weather Review*, vol. 84, No. 11, Nov. 1956, pp. 391–400.
5. G. E. Dunn, "Tropical Cyclones," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 887–901.
6. W. H. Klein and J. S. Winston, "Geographical Frequency of Troughs and Ridges on Mean 700-mb. Charts," *Monthly Weather Review*, vol. 86, No. 9, Sept. 1958, pp. 344–358.
7. J. Namias, "The Annual Course of Month-to-Month Persistence in Climatic Anomalies," *Bulletin of the American Meteorological Society*, vol. 33, No. 7, Sept. 1952, pp. 279–285.
8. J. Namias, "Quasi-Periodic Cyclogenesis in Relation to the General Circulation," *Tellus*, vol. VI, No. 1, Feb. 1954, pp. 8–22.
9. H. K. Saylor and R. J. Caporaso, "Development of a Large-Amplitude 500-mb. Trough in Western United States and Associated Surface Cyclogenesis, November 13–18, 1958," *Monthly Weather Review*, vol. 86, No. 11, Nov. 1958, pp. 447–456.
10. C. M. Woffinden, "The Weather and Circulation of November 1957—A Stormy Month with a Deep Trough over Central North America," *Monthly Weather Review*, vol. 85, No. 11, Nov. 1957, pp. 367–372.

DEVELOPMENT OF A LARGE-AMPLITUDE 500-MB. TROUGH IN WESTERN UNITED STATES AND ASSOCIATED SURFACE CYCLOGENESIS, NOVEMBER 13–18, 1958

HARLAN K. SAYLOR AND ROCCO J. CAPORASO

National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

During the period from November 13 to 18, 1958, a major upheaval in the zonal index over the United States took place, followed by a relatively rapid change to near normal conditions. This development was responsible for extremes in temperature over southwestern and southeastern United States; heavy snows in the Rocky Mountains and the north and west-central Plains regions; and an intense, rapid cyclogenesis over central United States. A rash of tornadoes and high wind storms occurred from north-central Texas into west-central Illinois on November 17 in intimate association with the cyclogenesis and the advancing cold front.

Some of the vital statistics of the period are shown in figure 1. When considering figure 1, one is immediately impressed with the large area over which the extremes in weather occurred. An interesting point is that the broad features of the upper circulation and the mean position of the major frontal zone during the period can be diagnosed without additional information.

The purpose of this brief article is to describe by use of 1000-mb., 500-mb., and 1000–500-mb. thickness charts

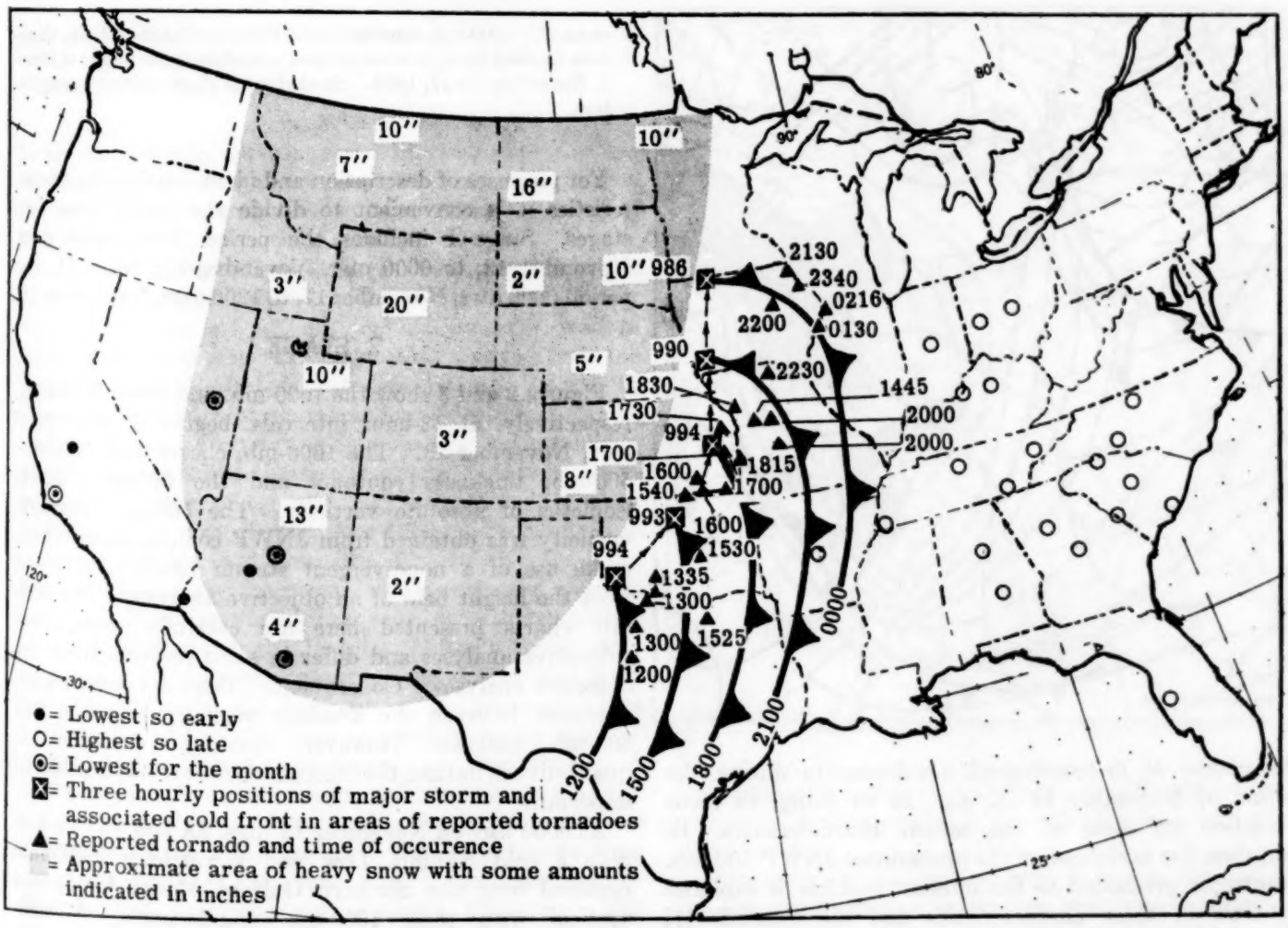


FIGURE 1.—Extremes in weather that occurred over the United States during the period November 15 to 19, 1958.

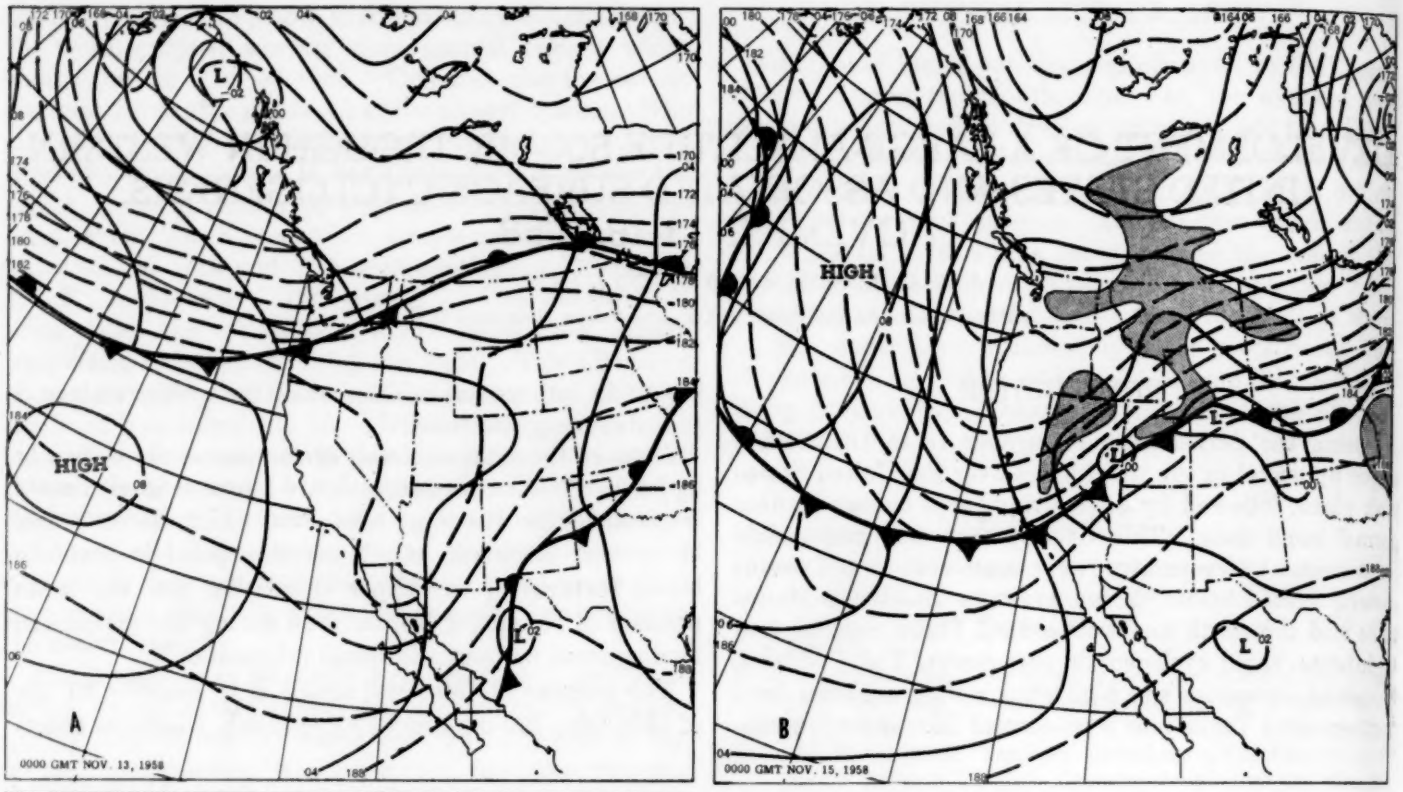


FIGURE 2.—1000-mb. contours (solid lines) and 1000–500-mb. thickness (dashed lines, labeled in hundreds of feet) for period of Stage I, November 13–17, 1958. Shaded areas show current precipitation.

the course of meteorological developments during the period of November 13–18, and, in so doing, to focus attention on some of the salient characteristics. In addition, the usefulness of the operational JNWP 500-mb. barotropic prediction to the forecast problem is explored in view of these characteristics and the Sutcliffe [1] development equation.

For purposes of description and identification of characteristics it is convenient to divide the period into two stages. Stage I includes the period from 0000 GMT, November 13, to 0000 GMT, November 17; Stage II, the period 0000 GMT, November 17, to 1200 GMT, November 18.

2. STAGE I

Figures 2 and 3 show the 1000-mb. and 500-mb. charts, respectively, at 48-hour intervals, beginning with 0000 GMT, November 13. The 1000-mb. charts include 1000–500-mb. thickness contours and the 500-mb. charts isopleths of absolute vorticity. The 500-mb. absolute vorticity was obtained from JNWP computations which make use of a nondivergent stream function obtained from the height field of an objective analysis. The 500-mb. charts presented here are carefully constructed subjective analyses and differ in some respects from the objective analyses. Consequently, there are some inconsistencies between the absolute vorticity isopleths and 500-mb. analyses. However, since the discussion is qualitative in nature, the inconsistencies are not considered important.

At 0000 GMT on November 13 (figs. 2A and 3A) we first note a cold 500-mb. Low and a vorticity maximum centered over the northern Gulf of Alaska just about vertical with their 1000-mb. counterparts. A well-defined frontal zone at both the 1000-mb. and 500-mb.

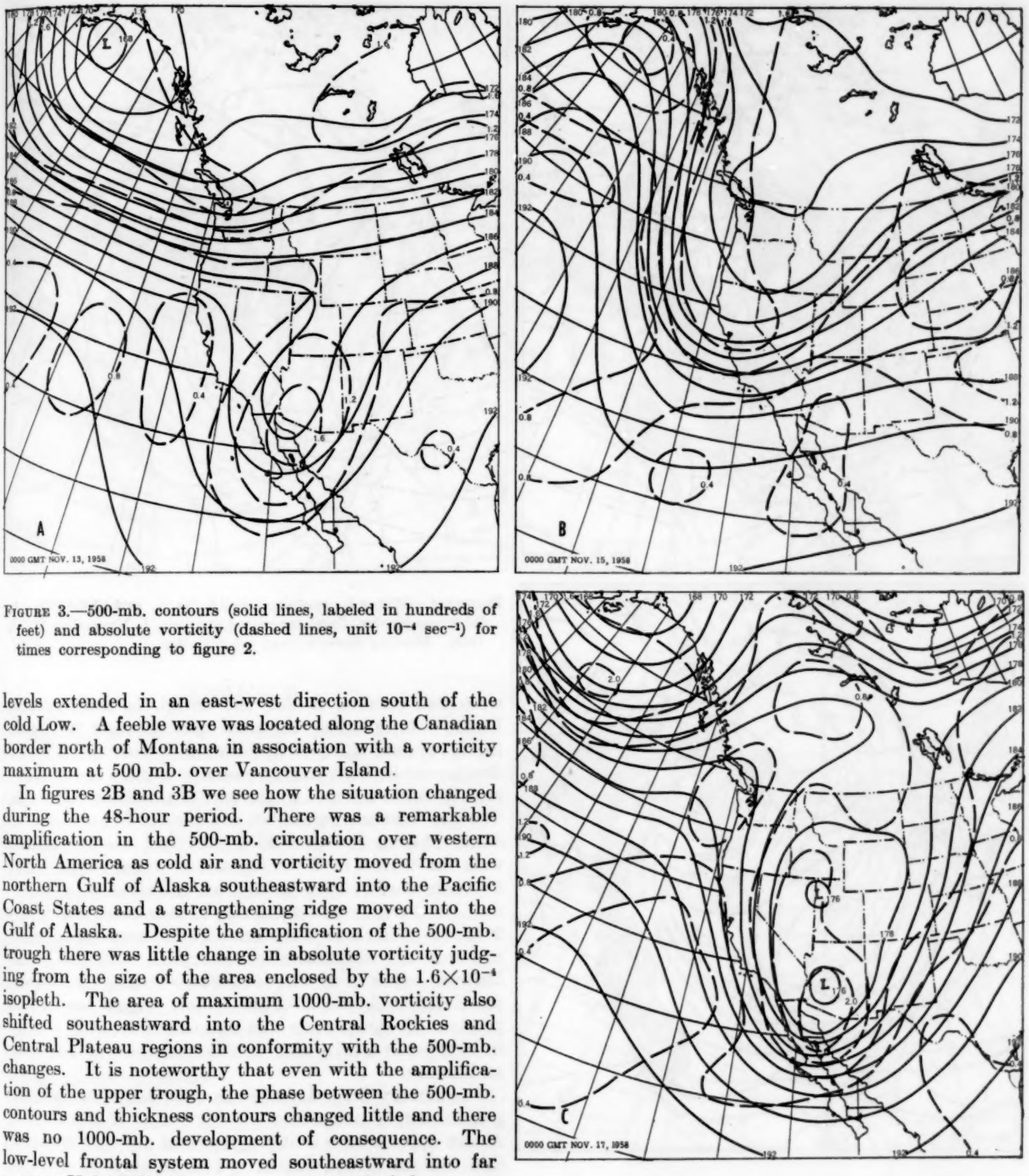


FIGURE 3.—500-mb. contours (solid lines, labeled in hundreds of feet) and absolute vorticity (dashed lines, unit 10^{-4} sec^{-1}) for times corresponding to figure 2.

levels extended in an east-west direction south of the cold Low. A feeble wave was located along the Canadian border north of Montana in association with a vorticity maximum at 500 mb. over Vancouver Island.

In figures 2B and 3B we see how the situation changed during the 48-hour period. There was a remarkable amplification in the 500-mb. circulation over western North America as cold air and vorticity moved from the northern Gulf of Alaska southeastward into the Pacific Coast States and a strengthening ridge moved into the Gulf of Alaska. Despite the amplification of the 500-mb. trough there was little change in absolute vorticity judging from the size of the area enclosed by the 1.6×10^{-4} isopleth. The area of maximum 1000-mb. vorticity also shifted southeastward into the Central Rockies and Central Plateau regions in conformity with the 500-mb. changes. It is noteworthy that even with the amplification of the upper trough, the phase between the 500-mb. contours and thickness contours changed little and there was no 1000-mb. development of consequence. The low-level frontal system moved southeastward into far western United States at an average speed of close to 15 knots, which is in strict concert with the average gradient directed normal to the front during the 48 hours and the movement of the upper trough. Two Low centers were in evidence along the front, one in extreme eastern Nevada and the other in southern Wyoming. The Nevada center was associated with the 500-mb. vorticity maximum over northern California, the Wyoming center with the flat thickness ridge through Colorado, Wyoming, and Montana.

Forty-eight hours later, we see, in figures 2C and 3C, the upper trough had undergone still further amplification and its progression eastward had slowed over the

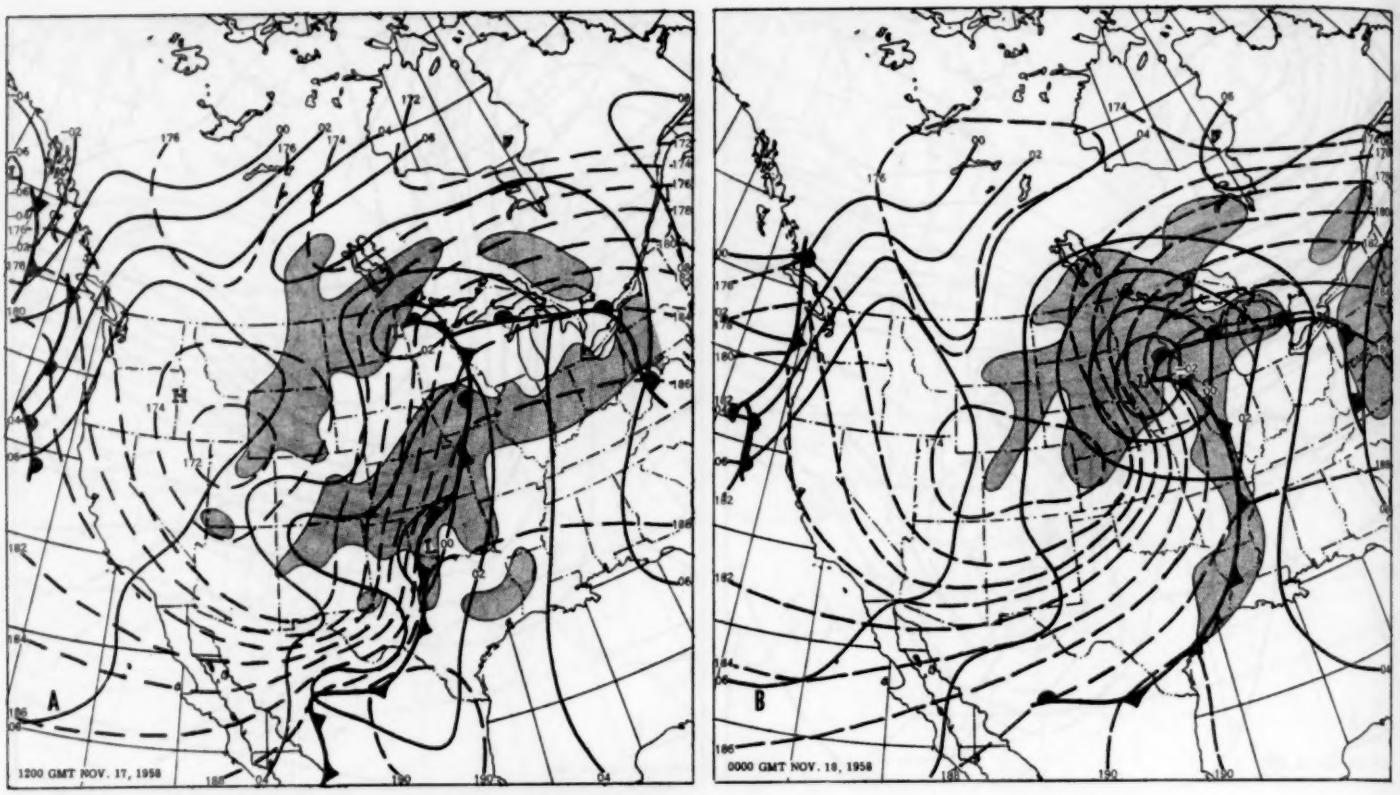


FIGURE 4.—1000-mb. contours (solid lines) and 1000–500-mb. thickness (dashed lines) for period of stage II, November 17–18, 1958. Shading shows current precipitation.

previous 48-hour period. A definite increase in vorticity was noted in the base of the trough. The jet stream reached its minimum latitude at roughly this time. The strong Gulf of Alaska ridge had weakened and moved to just off the Pacific Northwest coast, serving both to decrease the half-wave length and to increase the mean westerlies between it and the trough in southwestern United States. The thickness pattern and 1000-mb. frontal system changed in accordance with the 500-mb. developments, both having assumed a more north-south orientation in the area to the east of the 500-mb. trough. The two Low centers at 1000 mb. located in northeastern South Dakota and near El Paso, Tex., are identifiable with the centers in Wyoming and Nevada, respectively, 48 hours earlier, even though an examination of intermediate charts reveals continuity of movement during the 2 days is difficult to maintain. The measure of identification is the thickness ridge associated with the South Dakota center and the 500-mb. vorticity maximum associated with the El Paso center. Again, as in the previous 48 hours, there was comparatively little change in 1000-mb. vorticity although the change was definitely an increase.

In summary, Stage I can be characterized as follows: the gradual amplification over a 4-day period of the Gulf of Alaska upper trough as it progressed at a decelerated rate into western United States. This resulted in a major outbreak of cold air into southwestern United States. Throughout the 4 days the change in 1000-mb. vorticity associated with the 500-mb. trough was small.

In a broad sense the lower-level vorticity existing over the Northern Plains and southern Rockies at the end of the period can be looked upon as having gotten there from the northern Gulf of Alaska by translation.

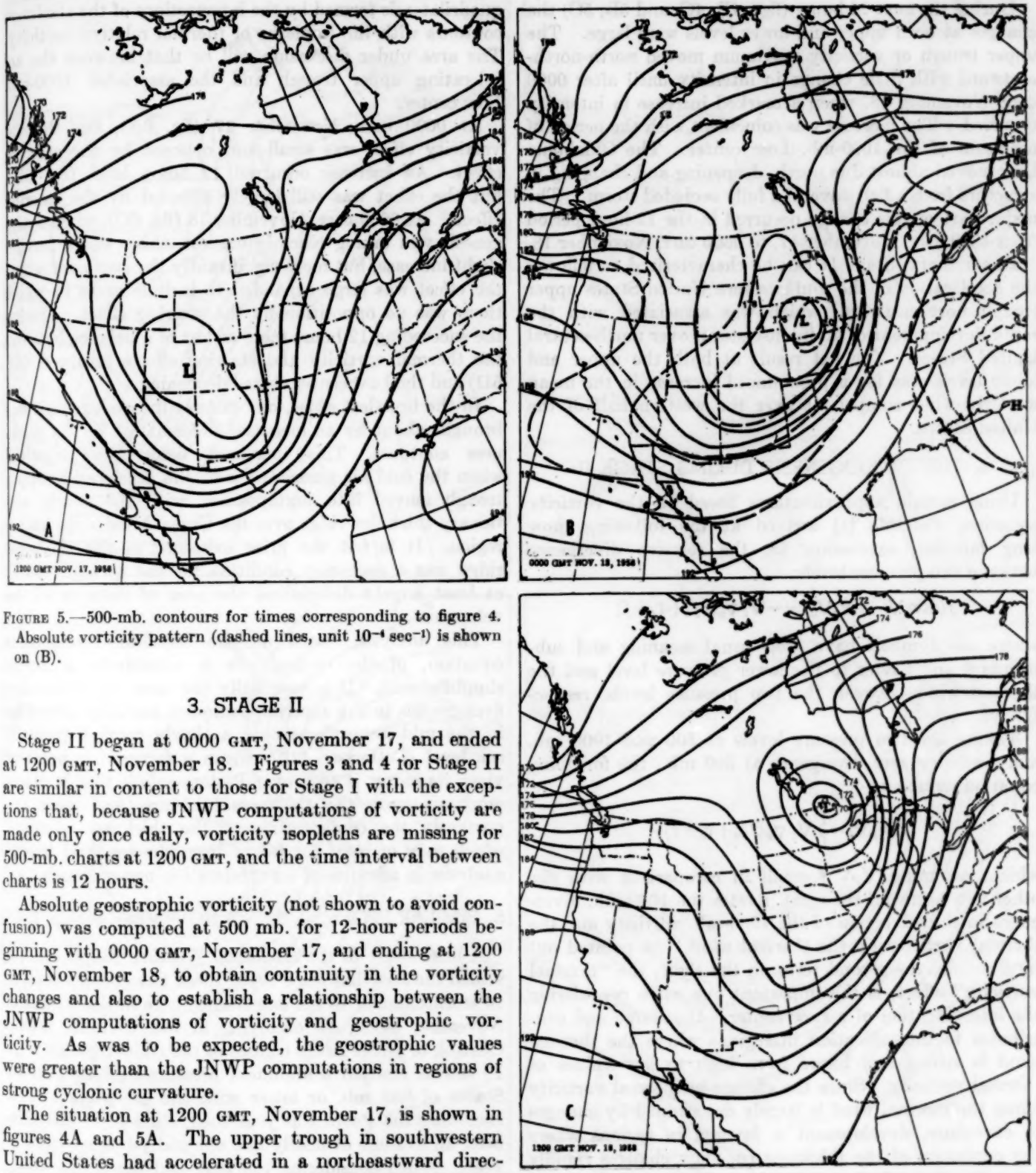


FIGURE 5.—500-mb. contours for times corresponding to figure 4. Absolute vorticity pattern (dashed lines, unit 10^{-4} sec^{-1}) is shown on (B).

3. STAGE II

Stage II began at 0000 GMT, November 17, and ended at 1200 GMT, November 18. Figures 3 and 4 for Stage II are similar in content to those for Stage I with the exceptions that, because JNWP computations of vorticity are made only once daily, vorticity isopleths are missing for 500-mb. charts at 1200 GMT, and the time interval between charts is 12 hours.

Absolute geostrophic vorticity (not shown to avoid confusion) was computed at 500 mb. for 12-hour periods beginning with 0000 GMT, November 17, and ending at 1200 GMT, November 18, to obtain continuity in the vorticity changes and also to establish a relationship between the JNWP computations of vorticity and geostrophic vorticity. As was to be expected, the geostrophic values were greater than the JNWP computations in regions of strong cyclonic curvature.

The situation at 1200 GMT, November 17, is shown in figures 4A and 5A. The upper trough in southwestern United States had accelerated in a northeastward direction, moving nearly as far in 12 hours as it had the previous 48 hours. The upper ridge along the west coast had continued to weaken and move eastward. At 1000 mb. the El Paso Low center had also accelerated and with little change in intensity moved to extreme southwestern Oklahoma. The frontal system extending from Iowa to northern Mexico was unusually strong, as can be seen from the thickness contours and the convergence of the 1000-mb. wind along the front. Surface temperature differences through the front in the vicinity of the Low were as much as 40° F. in 100 miles. Surface pressure tendencies at this time suggested the beginning of deepening for the Oklahoma Low. The South Dakota Low center had moved very slowly and was still associated with a pronounced thickness ridge.

During the next 24 hours (figs. 4B, 4C, and 5B, 5C) the changes at both upper and lower levels were large. The upper trough or vorticity maximum moved north-northeastward with little change in intensity until after 0000 GMT, November 18, when a marked increase in intensity occurred. The increase was coincident with the period of occlusion of the 1000-mb. Low center. The Oklahoma Low moved almost due north, deepening and changing in structure from a flat wave to a fully occluded storm. The major part of this change occurred in the 12-hour period from 1800 GMT, November 17, to 0600 GMT, November 18.

In summary, Stage II can be characterized as follows: the acceleration of the southwestern United States upper trough northeastward, which was associated with the rapid development of an intense storm over north-central United States. The net result at both the upper and lower levels was for a pronounced increase in the mean westerly wind component over the western half of the United States.

4. THE CYCLOGENESIS DURING STAGE II

Using certain approximations based on the vorticity equation, Sutcliffe [1] arrived at the following, now long familiar, expression for the relative divergence between two pressure levels:

$$f(\mathrm{div}_p \mathbf{V} - \mathrm{div}_p \mathbf{V}_0) = -\mathbf{V}_t \cdot \nabla_p (2\zeta_0 + \zeta_t + f)$$

where the symbols have their usual meaning and subscripts 0 and t refer to the lower pressure level and the thermal wind between the two pressure levels, respectively.

Taking the two pressure levels at 500 and 1000 mb. and assuming zero divergence at 500 mb., the foregoing equation reduces to—

$$\mathrm{div}_p \mathbf{V}_0 = \frac{1}{f} \mathbf{V}_t \cdot \nabla_p (2\zeta_0 + \zeta_t + f)$$

which, assuming $\mathbf{V}_t \cdot \nabla f$ small in comparison with the other two terms on the right, relates the 1000-mb. divergence to the advection of the 1000-mb. vorticity and the thermal vorticity by the thermal wind. As pointed out by Sutcliffe, the second term on the right, the "thermal vorticity" effect, is the important one when considering the intensification of a Low center. It is large and contributes to intensification in regions where the thermal wind is strong and blows from high to low values of thermal vorticity. Since the change in thermal vorticity along the thermal wind is largely determined by changes in curvature, development is favored in regions where the curvature of the thickness contours changes rapidly from sharply cyclonic to sharply anticyclonic. It should also be noted that the term $\mathbf{V}_t \cdot \nabla_p \zeta_0$, which Sutcliffe calls the steering effect, normally balances or opposes the thermal vorticity effect.

Figure 6 shows in a qualitative manner the variation of the thermal vorticity effect at 12-hour intervals beginning with 0000 GMT, November 17. The magnitude of the effect is inversely proportional to the size of the quadrilaterals formed by the intersections of the thickness contours with the isopleths of thermal relative vorticity. The area under discussion will be that between the accelerating upper trough and the associated 1000-mb. Low center.

At 0000 GMT, November 17 (fig. 6A), the thermal vorticity effect was small and opposed by the steering effect. An increase occurred 12 hours later (fig. 6B), but the effect was still largely opposed by the steering effect. At 0000 GMT, November 18 (fig. 6C), when cyclogenesis was taking place in earnest, there was a further slight increase, but more significantly the area over which the effect was large expanded to include areas in which there was no opposition by the steering effect. During the succeeding 12 hours more or less of a balance between the thermal vorticity and steering effects returned (fig. 6D) and the Low center ceased deepening.

In the broadest sense, one can say the cyclogenesis was brought about by an increased deformation of the thickness contours. This increased deformation resulted when the cold air associated with the accelerating upper trough moved into juxtaposition with the nearly stationary thickness ridge over the Upper Mississippi Valley region. It is felt the prior existence of the thickness ridge was a necessary condition for the cyclogenesis or at least largely determined the area of most rapid development.

This analysis, based on the Sutcliffe development equation, of the cyclogenesis is admittedly a highly simplified one. It is essentially the same as attributing cyclogenesis to the superimposition of vorticity advection in the mid-troposphere over a slowly moving front at sea level (Petterssen [2]). From a forecasting point of view, its merit, if any, over Petterssen's is that it places emphasis upon the thickness contours, and more importantly the configuration of the thickness contours, which may or may not follow from the sea level frontal analysis, in advance of an accelerating upper trough.

5. SIMILAR STORMS DURING NOVEMBER SINCE 1945

A brief study of the Historical Weather Map series revealed the fact that since 1945[1] there have been a total of 10 storms similar to the one studied here in the month of November alone, all occurring in the Central, North-Central, or Great Lakes regions of the United States. All 10 storms reached a minimum pressure over the United States of 985 mb. or lower with the exception of one. Including the storm this year then, since 1945 there has been an average of nearly one unusually intense storm a year. When considering the time and space limitations and also the intensity requirement for inclusion in the list, this is truly an amazing fact. It is almost as if the atmosphere announces the beginning of winter over central United States in November by a spectacular cyclogenesis. Following are the dates on which this announcement has been made:

[1] Study limited to years in which 500-mb. charts were available.

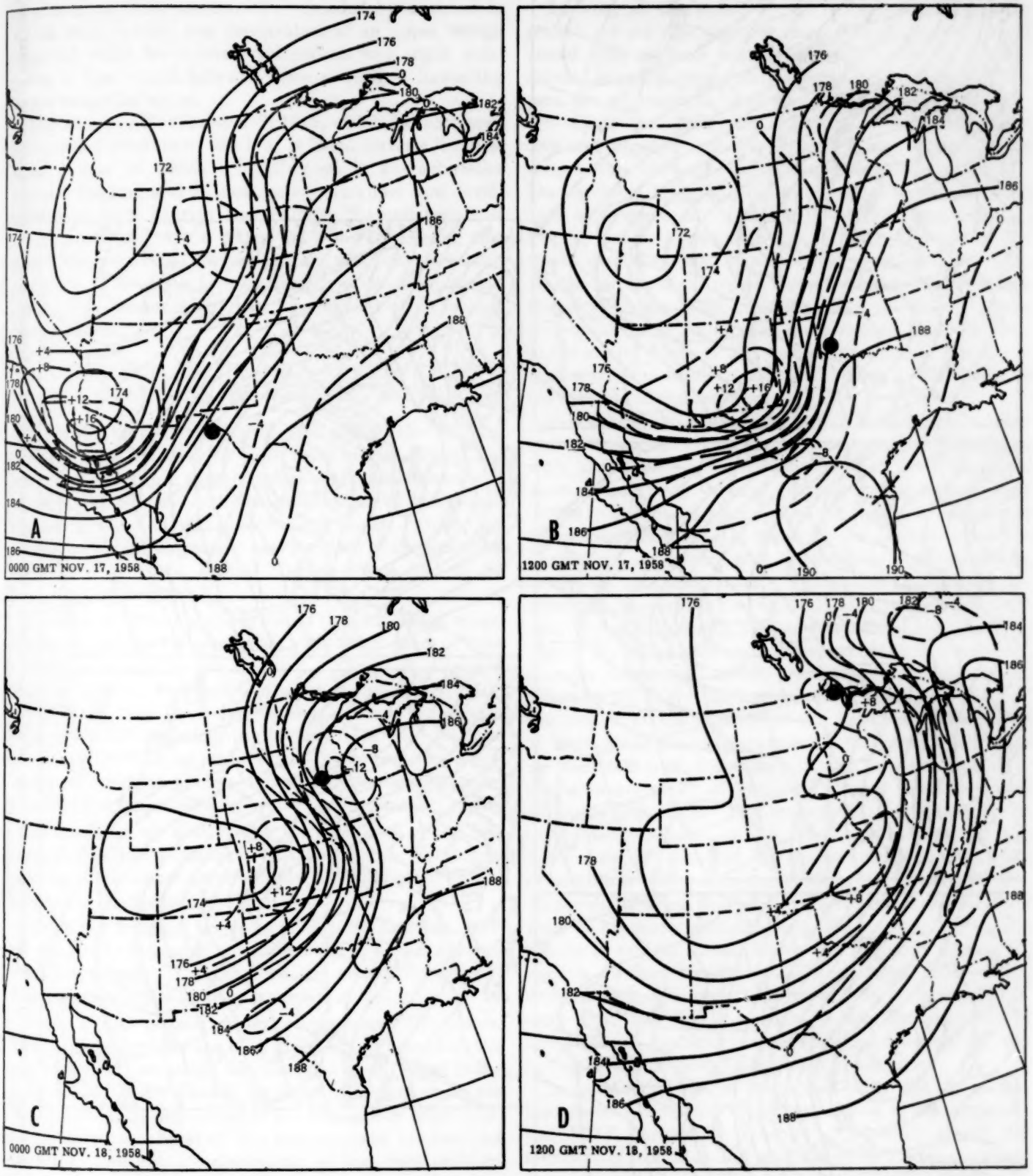


FIGURE 6.—Variations in Sutcliffe's thermal vorticity effect during Stage II. 1000–500-mb. thickness contours (solid lines, labeled in hundreds of feet) and the Laplacian of the thickness (dashed lines, relative units). Black dot indicates position of Low center.

November 13, 1945.
November 6–7, 1946.
November 22, 1946.
November 7–8, 1947.
November 5–6, 1948.
November 14, 1951.
November 25–26, 1952.
November 16–17, 1955.
November 21, 1956.
November 19, 1957.

All of these storms exhibited what can be termed two stages. The characteristics of the stages were similar to what has been described here, the primary difference being the difference in duration of Stages I and II. By way of

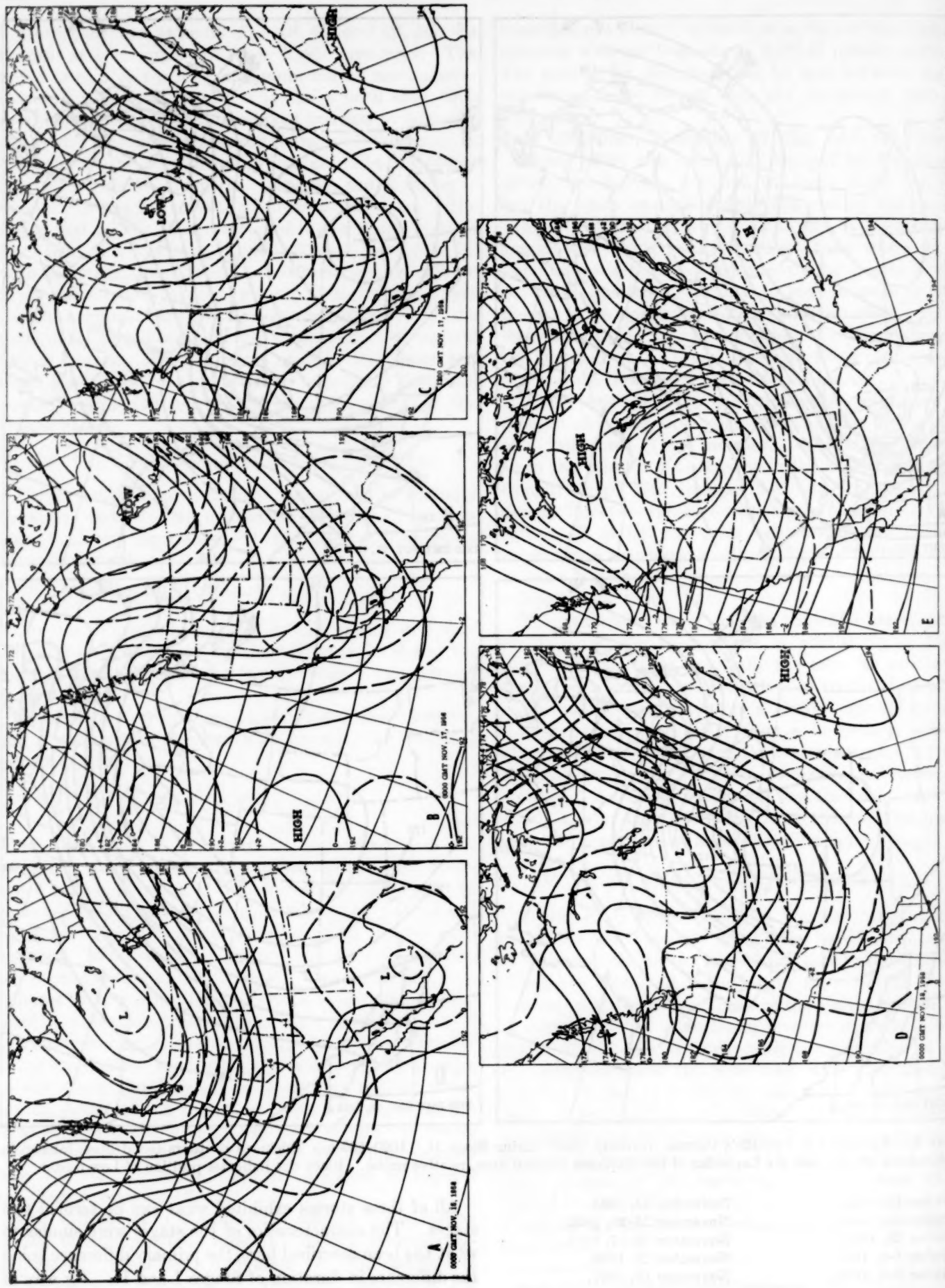


FIGURE 7.—48-hour barotropic 500-mb. JNWP prognostics (solid lines) for all times for which 500-mb. charts are shown in figures 3 and 5, with the exception of 0000 GMT, November 13. Dashed lines show error in hundreds of feet.

emphasis, all these storms were preceded by a period in which amplification and deceleration of an upper trough occurred while lower-level cyclogenesis was slight compared to that which followed when a trend to increasing upper westerlies set in.

The storm of November 6–7, 1946, which did not reach a minimum pressure of 985 mb., is listed because it represents a case in which the difference in characteristics between Stages I and II is extreme. An upper Low developed over New Mexico (see Palmén [3]) and remained nearly stationary for a period of 3 days. During this period the associated surface pattern was primarily anticyclonic. The upper Low eventually accelerated northeastward accompanied by the development of an intense surface storm.

6. USEFULNESS OF THE NWP 48-HOUR 500-MB. PROGNOSTIC TO THE FORECAST PROBLEM

According to the results of this study, the forecast problem may be divided into three parts. First, the growth of the upper trough in western United States had to be predicted. Second, the acceleration of the trough northeastward had to be accurately timed. Third, the favorable (for development) configuration of the thickness contours over north central United States had to be recognized or diagnosed.

Parts one and two of the problem have long been recognized by synoptic meteorologists with many years of forecasting experience in the Midwest. The U. S. Weather Bureau District Forecast Center at Kansas City, Mo., attempts to take these factors into account by certain objective rules applied to the 500-mb. level [4]. In spite of an awareness of the major points in the problem, meteorologists continue to have difficulty in presenting a forecast that has some degree of preciseness in time and space.

At this point we shall review the usefulness of the Numerical Weather Prediction 48-hour 500-mb. barotropic prognostic (hereafter called simply NWP forecast) to the solution of the forecast problem.

The NWP forecasts verifying at all times for which 500-mb. charts are presented in figures 3 and 5, with the exception of 0000 GMT, November 13, are shown in figure 7. Also included is the error in hundreds of feet.

First, a few general remarks concerning the errors. The barotropic model has been gradually improved to the point where it now seems, to those who are involved in the daily use of NWP forecasts, as if the remaining errors are largely caused by departures of the atmosphere from barotropic behavior. Most of this improvement has resulted from the following: (1) elimination of boundary problem errors through use of a hemispheric grid, (2) use of the so-called "balance equation" to obtain wind and vorticity at 500 mb. [5] which has eliminated the "blowup" or "spurious anticyclogenesis" problem, and (3) the stabilization of the very long atmospheric waves (Cressman [6]) which has done away with certain large-scale error patterns and greatly improved forecasts of 500-mb. height values.

Looking at the errors in NWP forecasts during this period, we see that positive errors were intimately associated with areas of cold-air advection and, to a lesser extent, negative errors with warm-air advection. Temperature advection is one common measure of baroclinicity. Note, especially, the positions of maximum positive and negative errors in figure 7B and compare with temperature advection patterns as indicated in figure 2C. During Stage I the position and sign of the errors were such as to result in a forecast of too little amplification. During the early part of Stage II the magnitude of the errors decreased but became large again at 1200 GMT, November 18, in the region of the cyclogenesis. Whereas the errors during Stage I did not affect the forecast accuracy of the upper trough position in western United States, at the end of Stage II the position and sign of the errors were such as to result in the trough being forecast slow at the latitude of the cyclogenesis.

In spite of the errors during this period, which were unusually large, a visual comparison of the NWP forecasts with the verifying charts reveals the NWP forecasts went a long way toward foretelling the sequence of events.[2] Of special interest are the forecasts during the transition from Stage I to Stage II; i. e., the change from increasing amplitude and deceleration to decreasing amplitude and acceleration. Comparing the forecast for 0000 GMT, November 15 (fig. 7A), with the one for 0000 GMT, November 17 (fig. 7B), in the area of southwestern United States, one can easily see the prediction of acceleration for the trough at the latitude of the jet stream. Whereas the NWP forecasts implied a displacement of the trough at the latitude of the jet stream of only 6° of longitude in the 48 hours between 0000 GMT, November 15, and 0000 GMT, November 17, the forecasts implied a displacement of 7° of longitude during the succeeding 12 hours (fig. 7C). The success of the forecast was undoubtedly related to the excellence with which the NWP forecasts handled the displacement and decrease in amplitude of the upstream ridge in the Eastern Pacific. (It should be added that all NWP forecasts of shorter time were in harmony with the foregoing.) Since the cyclogenesis in central United States was primarily dependent upon a forecast acceleration of the trough from southwestern United States, it might not be unreasonable to state that the NWP forecast, which by definition is incapable of predicting development, telegraphed the timing of this development 2 days in advance.

In summary, one is impressed with the following: that despite the highly baroclinic nature of the situation, the NWP barotropic forecasts told much about the sequence of events at 500 mb. and in turn at the surface. It seems as if the baroclinic effects throughout the period operated in the *framework* of a barotropic atmosphere. The baroclinic effects, even though large, acted to change only the *degree* of the barotropic developments and not the *substance*.

[2] This should be especially evident to meteorologists involved in producing forecasts during the period.

In view of the preceding paragraph, remarks by Rossby in 1949 [7] seem pertinent. Rossby stated, "Once a cold anticyclonic dome has been formed it may, through southward displacement and sinking, contribute materially to the intensification of the upper long-wave pattern and may lead to the formation of closed cyclonic centers aloft.[3] Nevertheless, several years of aerological experience indicate that the formation of such upper-level vortices is, to a considerable degree, predictable from the interaction between long waves aloft and from the general character of the flow pattern at these levels. We are thus led to the conclusion that the places where the formation of cold domes is initiated and where potential energy is released ultimately are determined by the upper long-wave pattern."

ACKNOWLEDGMENTS

The writers take this opportunity to thank the members of the Daily Map Unit of the Weather Bureau for drafting of the figures.

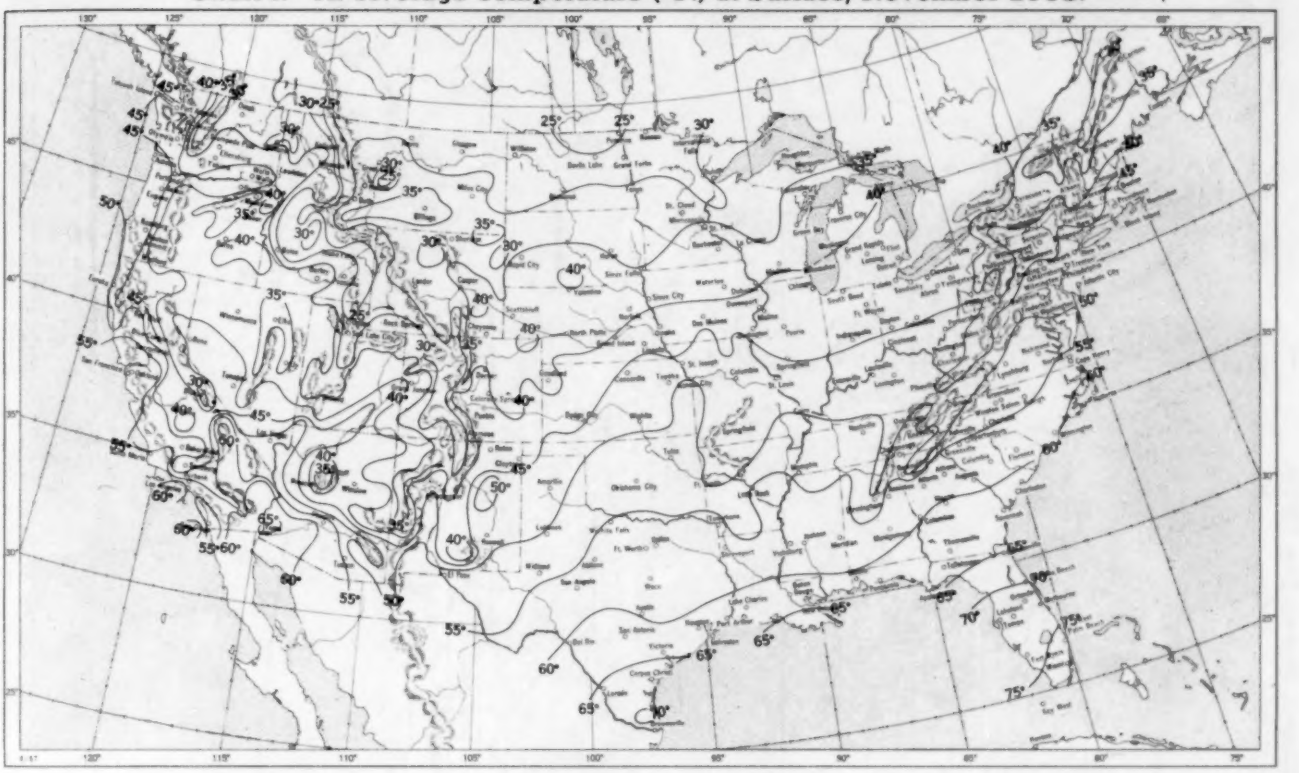
[3] This process appears to parallel closely the course of events during Stage I.

REFERENCES

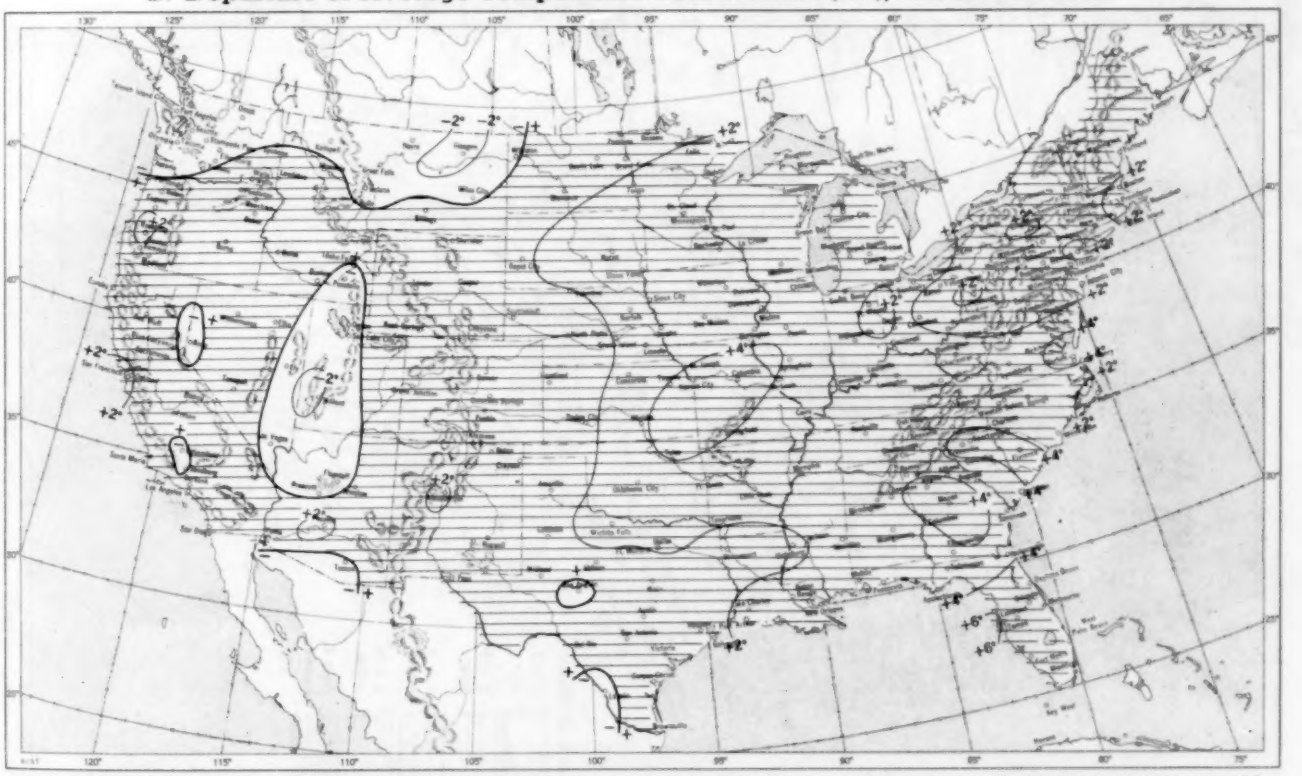
1. R. C. Sutcliffe, "A Contribution to the Problem of Development," *Quarterly Journal of the Royal Meteorological Society*, vol. 73, Nos. 317–318, 1947, pp. 370–383.
2. S. Petterssen, *Weather Analysis and Forecasting*, Second Edition, vol. I, McGraw-Hill Book Co., Inc., New York, 1956.
3. E. Palmén, "On the Origin and Structure of High Level Cyclones South of the Maximum Westerlies," *Tellus*, vol. 1, No. 1, 1949, pp. 22–31.
4. H. L. Jacobson, R. A. Sanders, and D. M. Hanson, "The Central High Plains Storm of November 1–3, 1956," *Monthly Weather Review*, vol. 85, No. 11, Nov. 1956, pp. 401–414.
5. Joint Numerical Weather Prediction Unit, *Bulletin No. 12*, effective Oct. 1, 1956.
6. G. P. Cressman, "Barotropic Divergence and Very Long Atmospheric Waves," *Monthly Weather Review*, vol. 86, No. 8, Aug. 1958, pp. 293–297.
7. C.-G. Rossby, "On a Mechanism for the Release of Potential Energy in the Atmosphere," *Journal of Meteorology*, vol. 6, No. 3, June 1949, pp. 163–180.

U. S. GOVERNMENT PRINTING OFFICE: 1959

Chart I. A. Average Temperature (°F.) at Surface, November 1958.



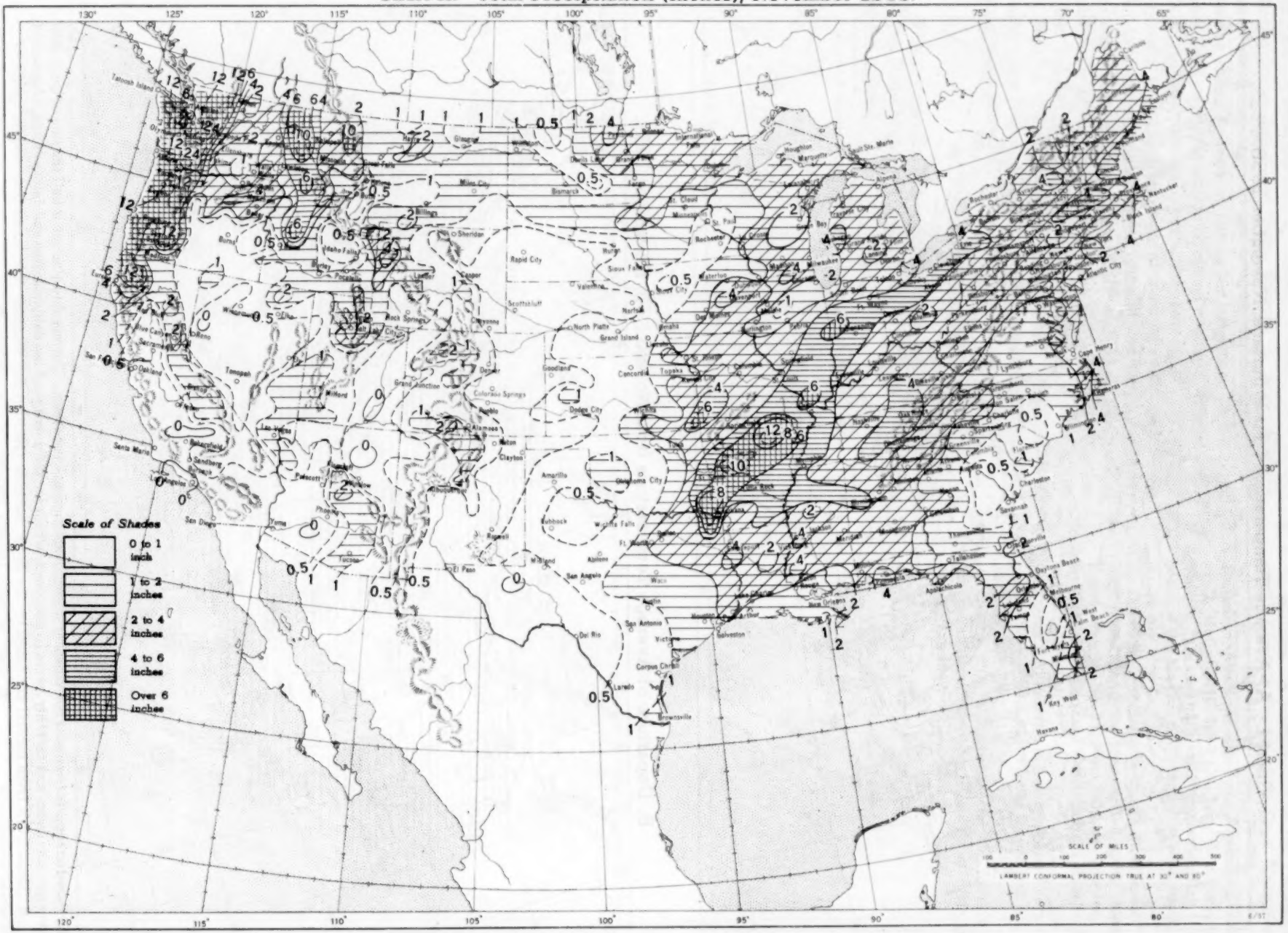
B. Departure of Average Temperature from Normal (°F.), November 1958.



A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

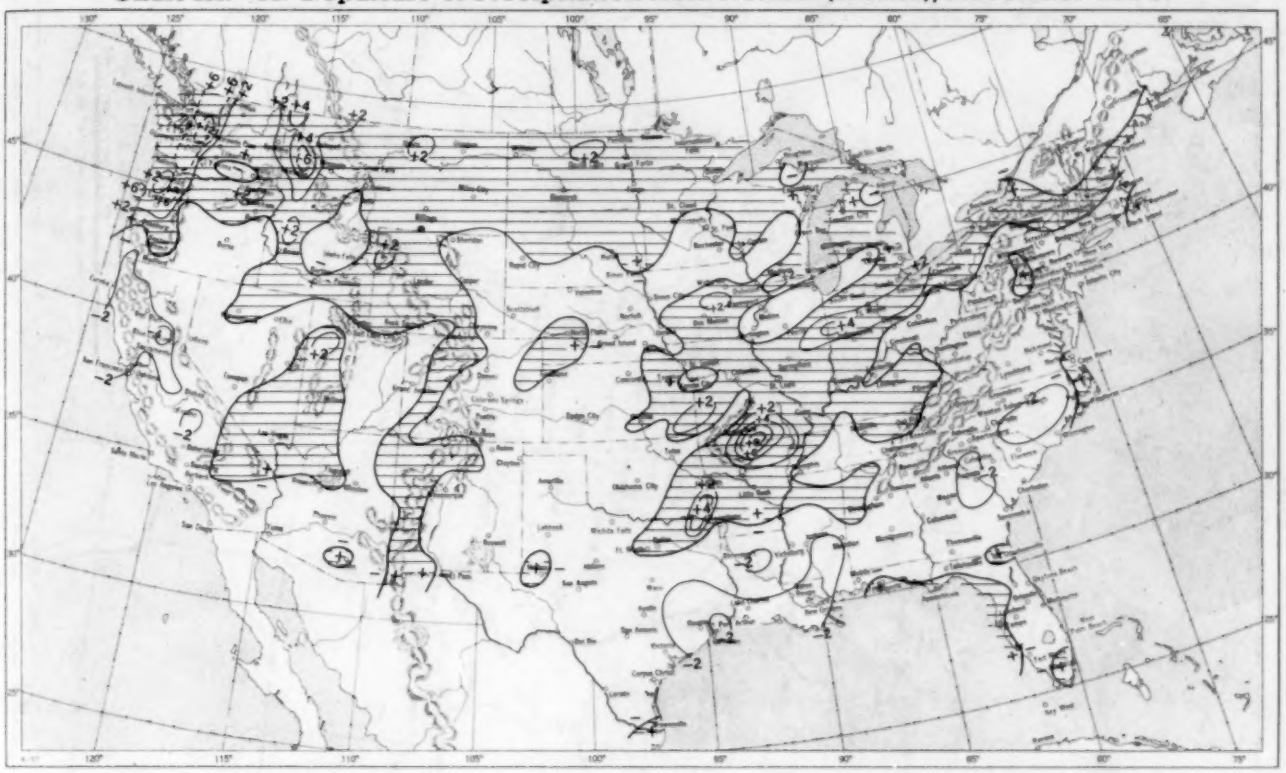
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

Chart II. Total Precipitation (Inches), November 1958.

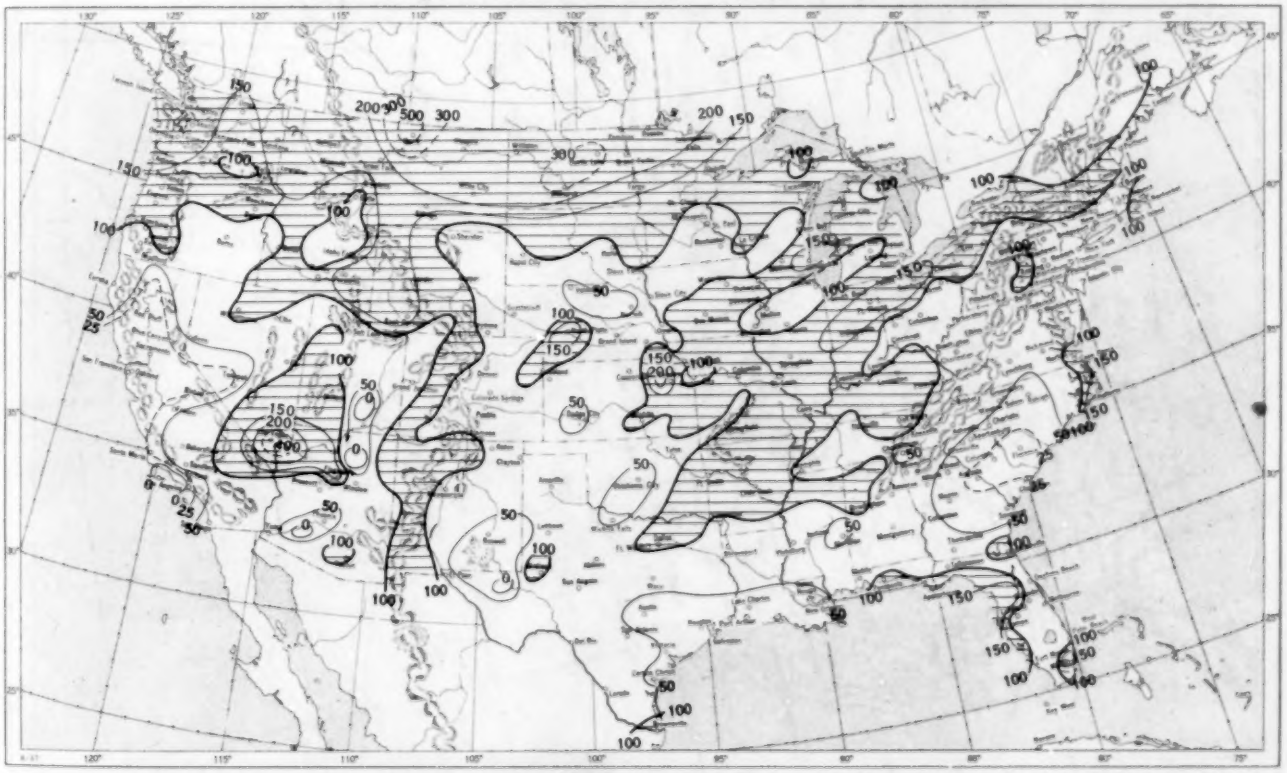

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 65°

Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), November 1958.

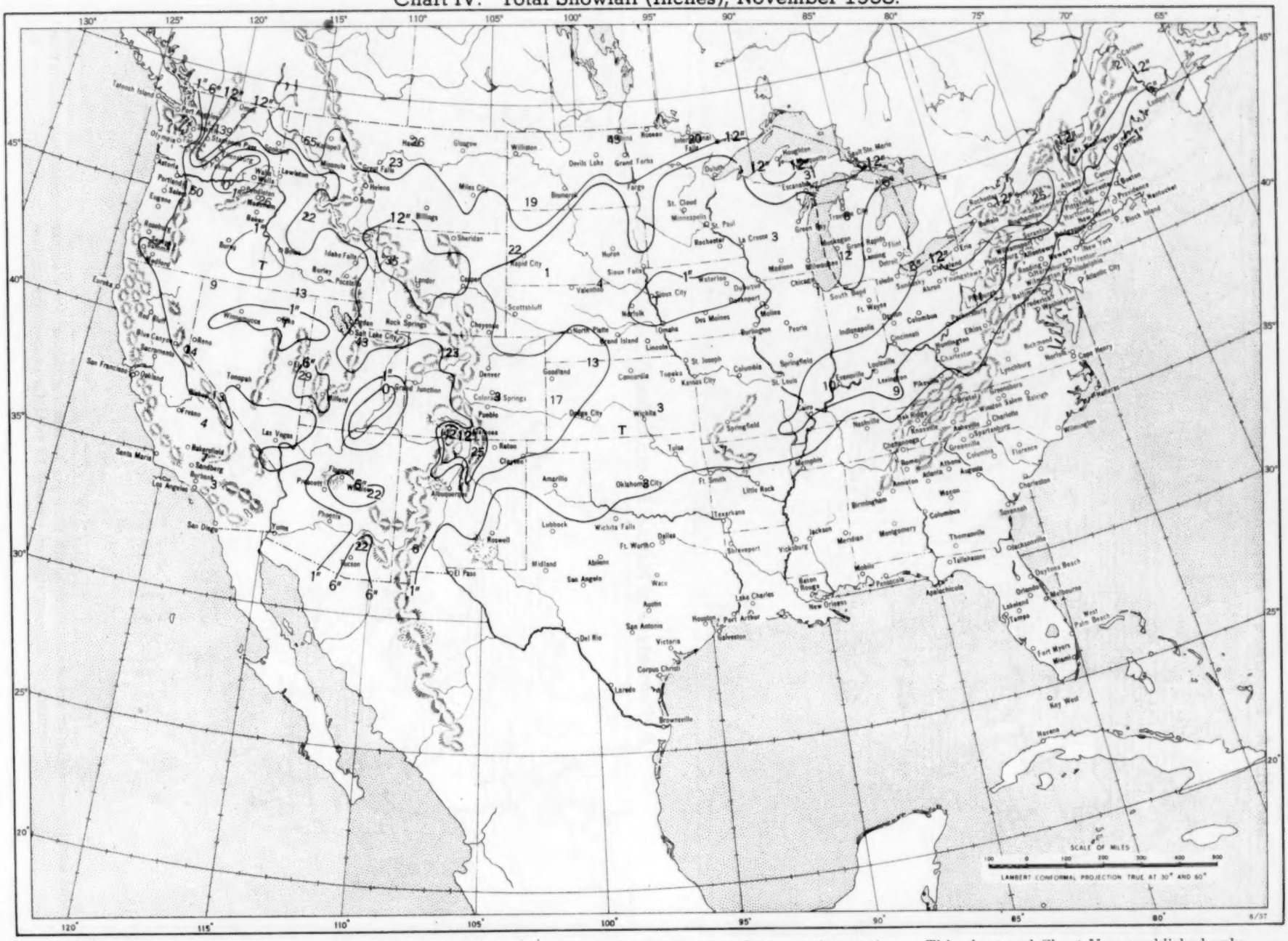


B. Percentage of Normal Precipitation, November 1958.



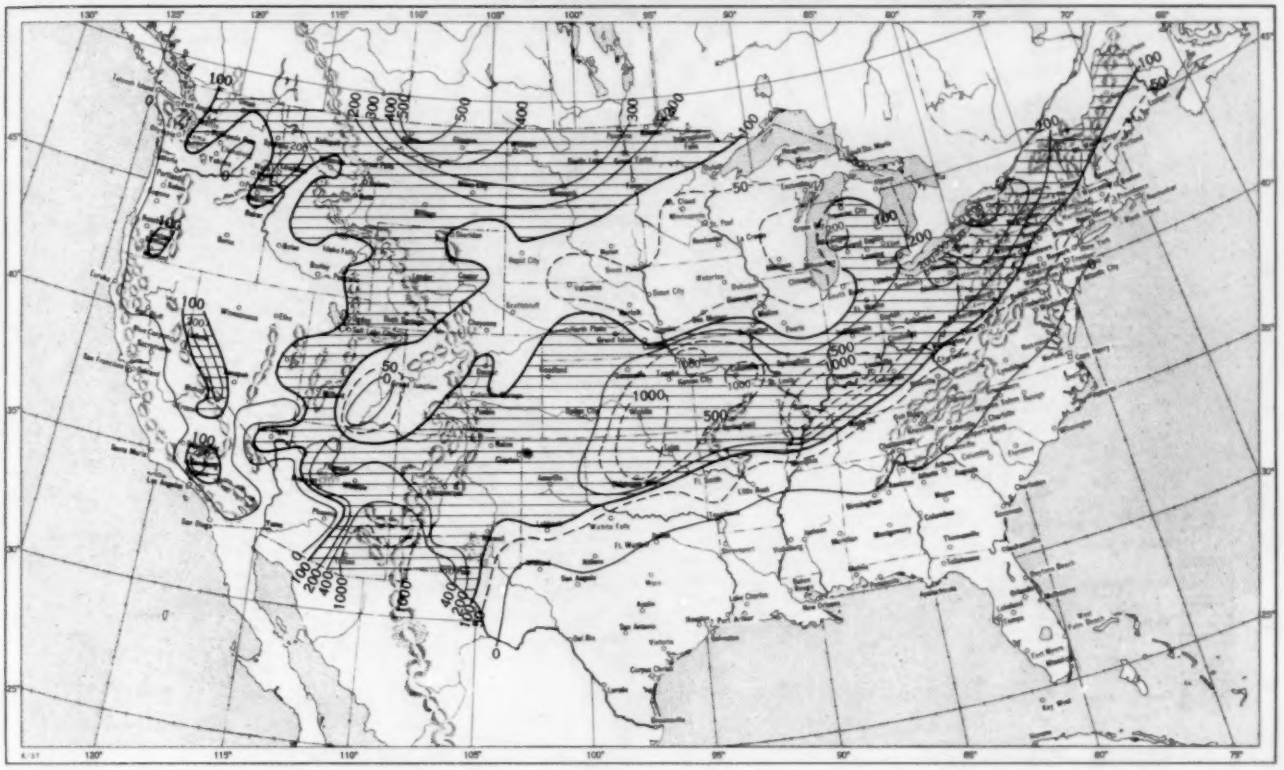
Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart IV. Total Snowfall (Inches), November 1958.

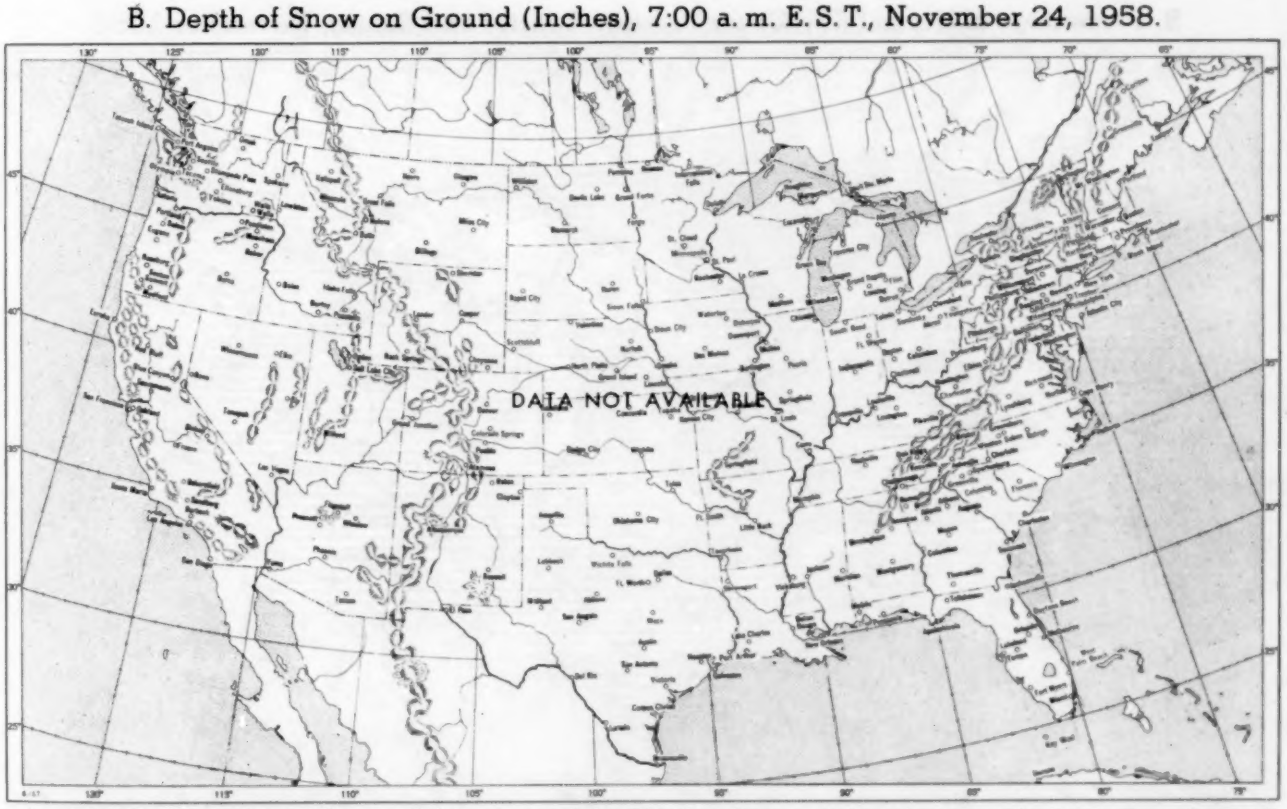


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, November 1958.

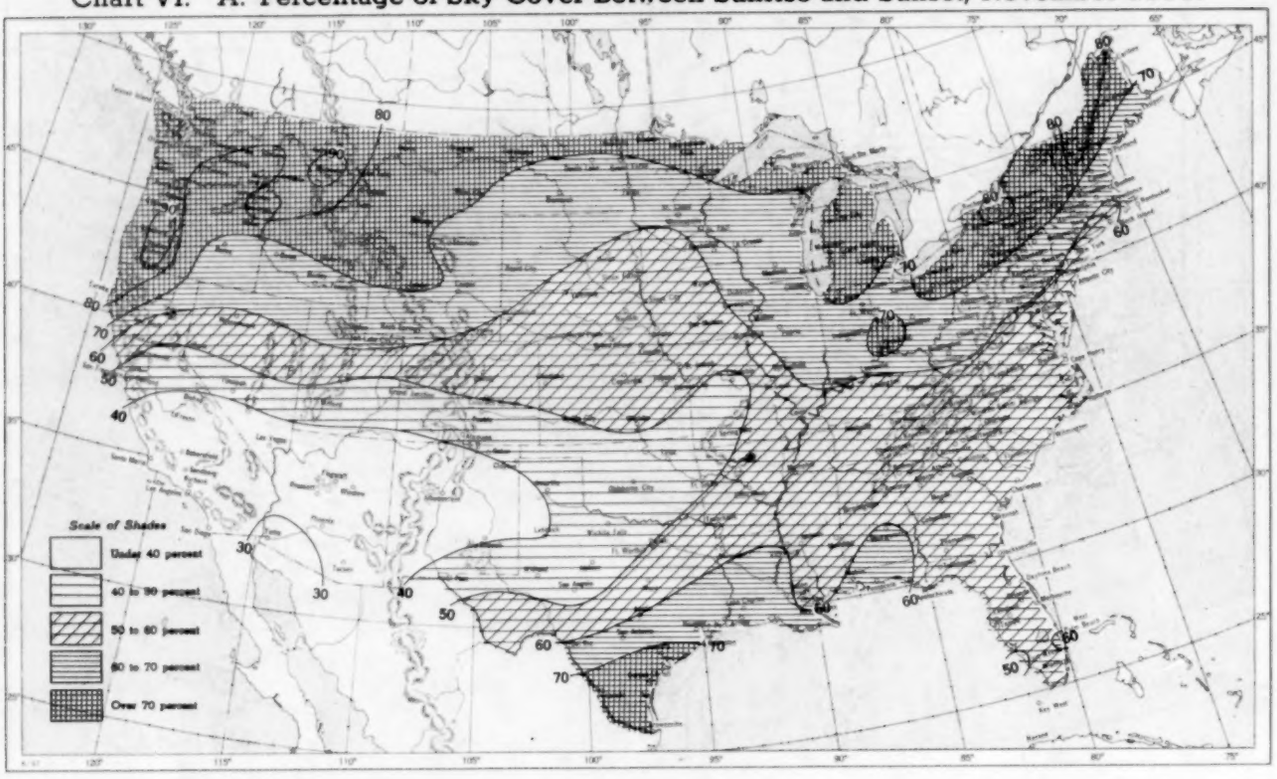


B. Depth of Snow on Ground (Inches), 7:00 a. m. E. S. T., November 24, 1958.

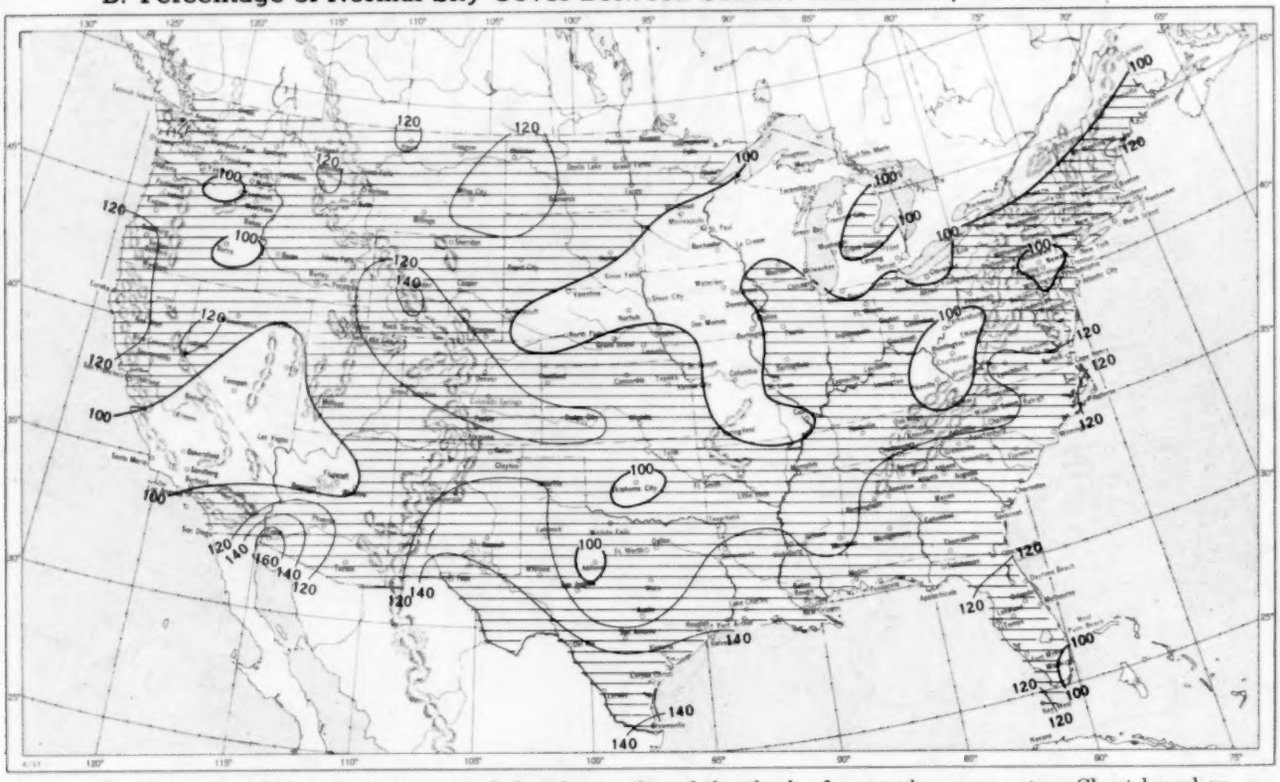


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:00 a.m. E.S.T., of the Monday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, November 1958.

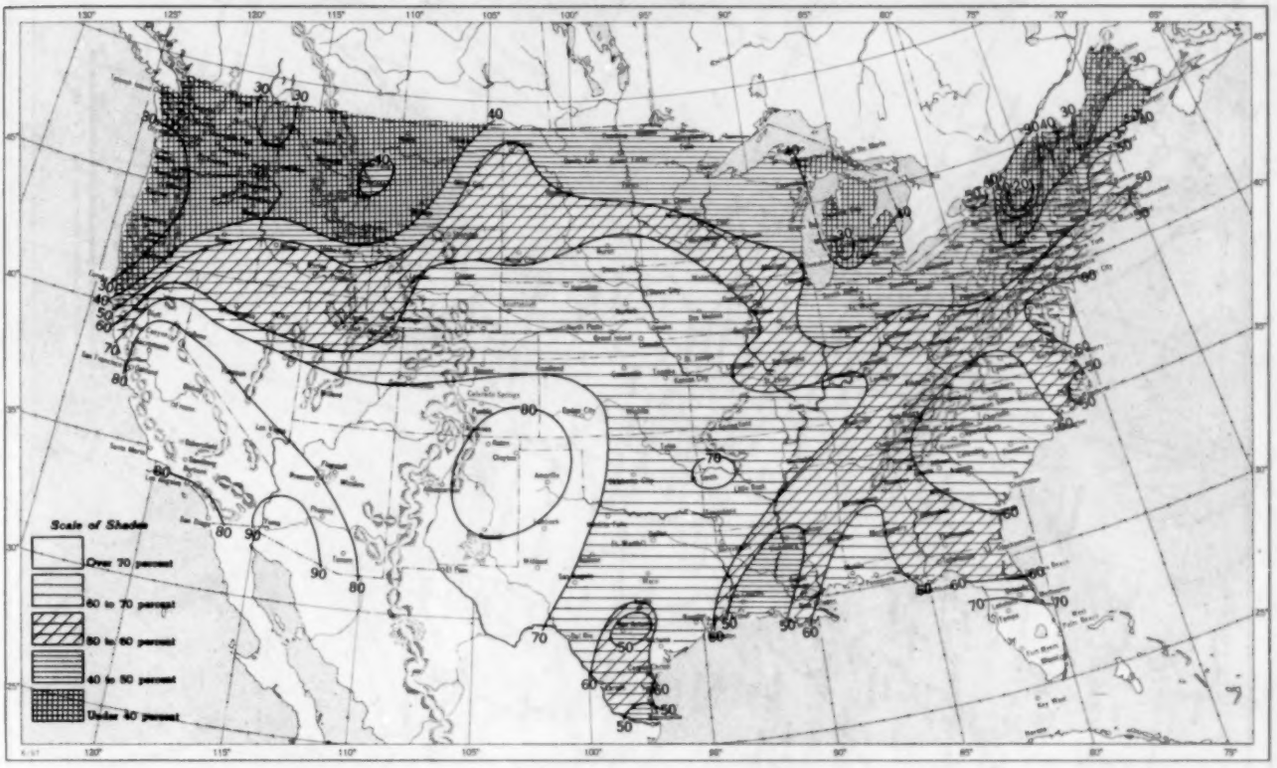


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, November 1958.

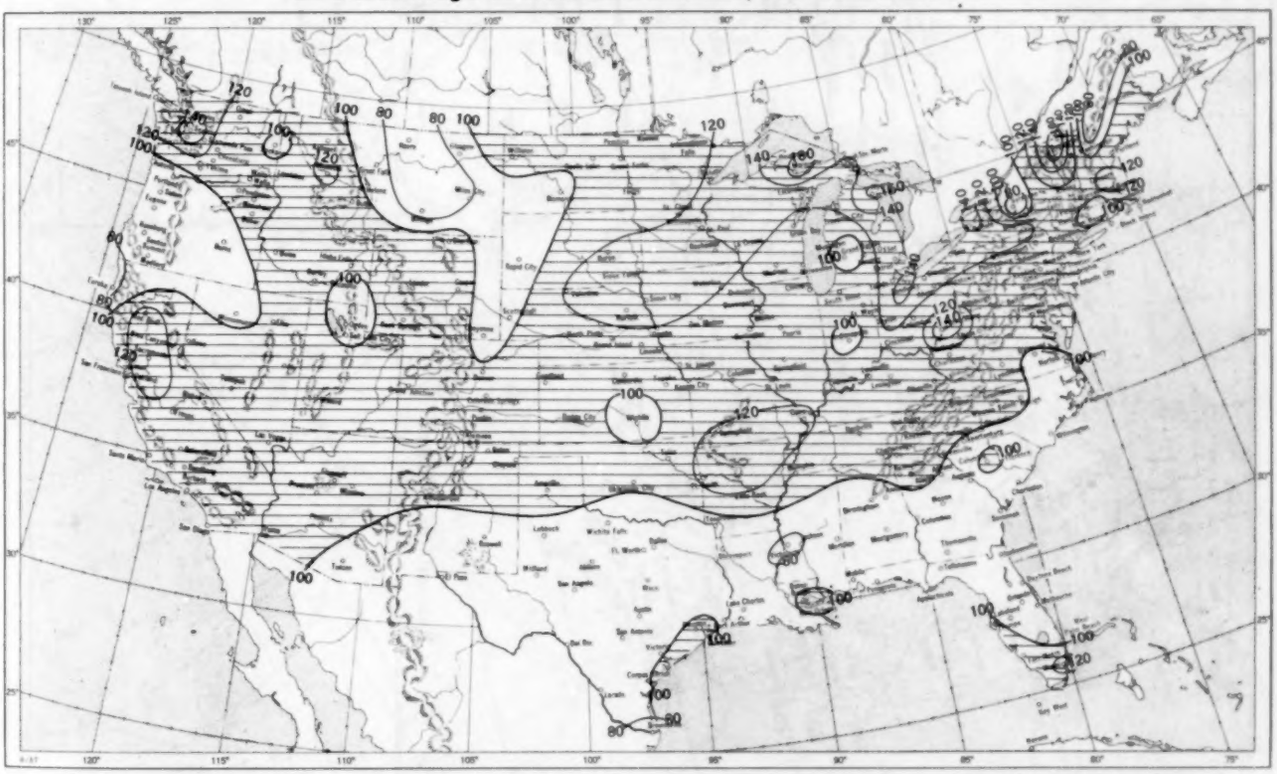


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, November 1958.



B. Percentage of Normal Sunshine, November 1958.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, November 1958. Inset: Percentage of Mean Daily Solar Radiation, November 1958. (Mean based on period 1951-55.)

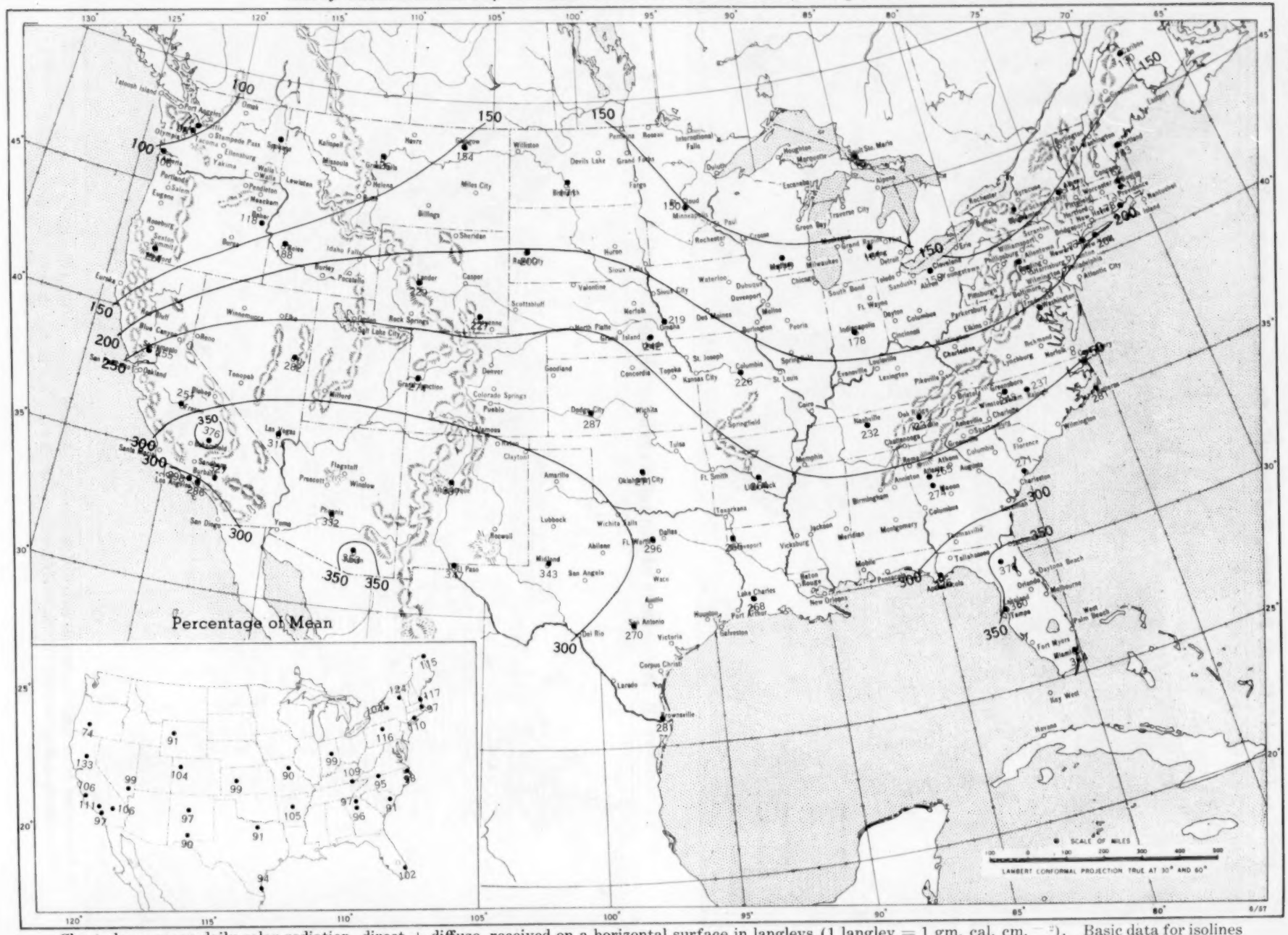
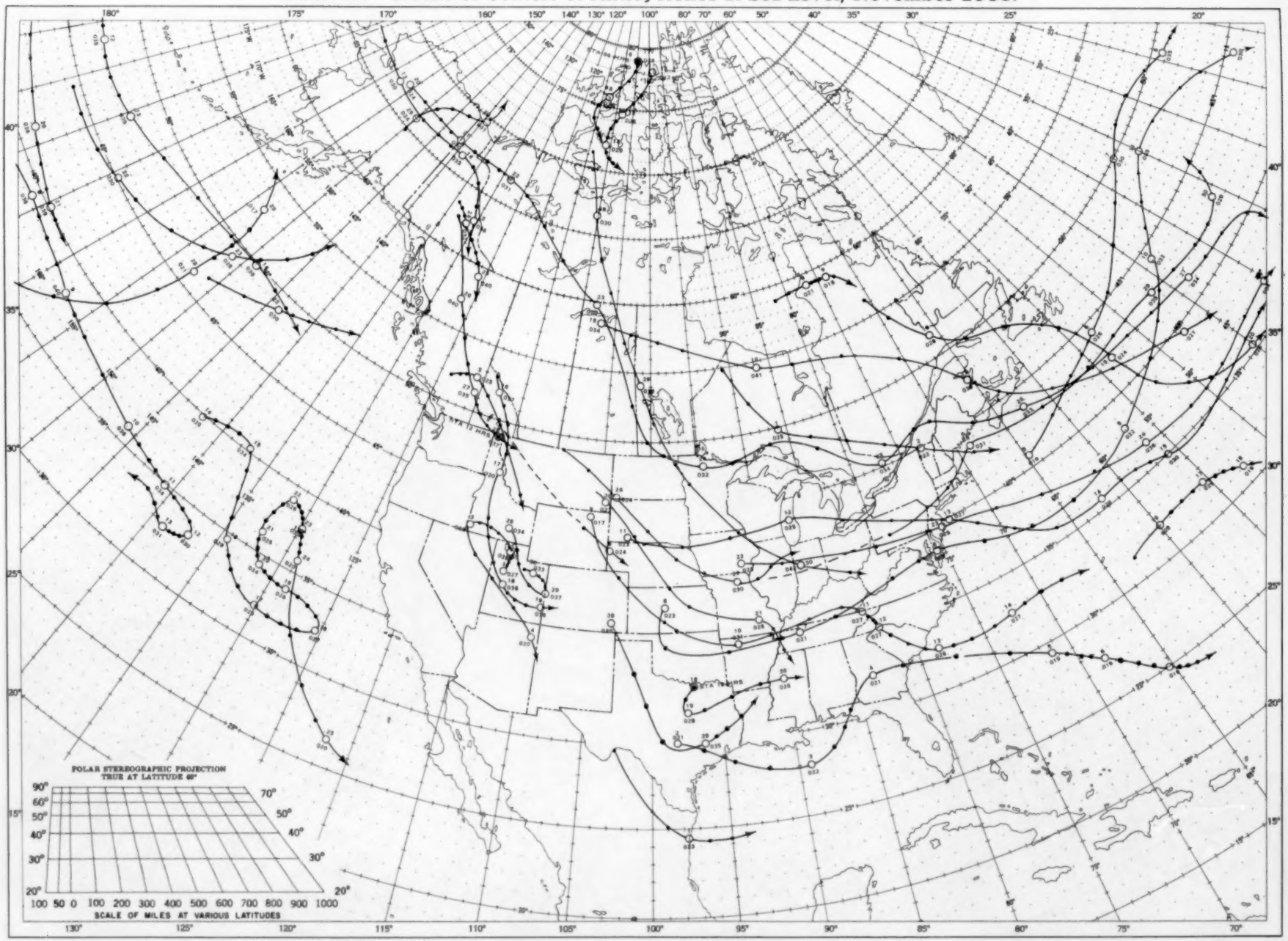


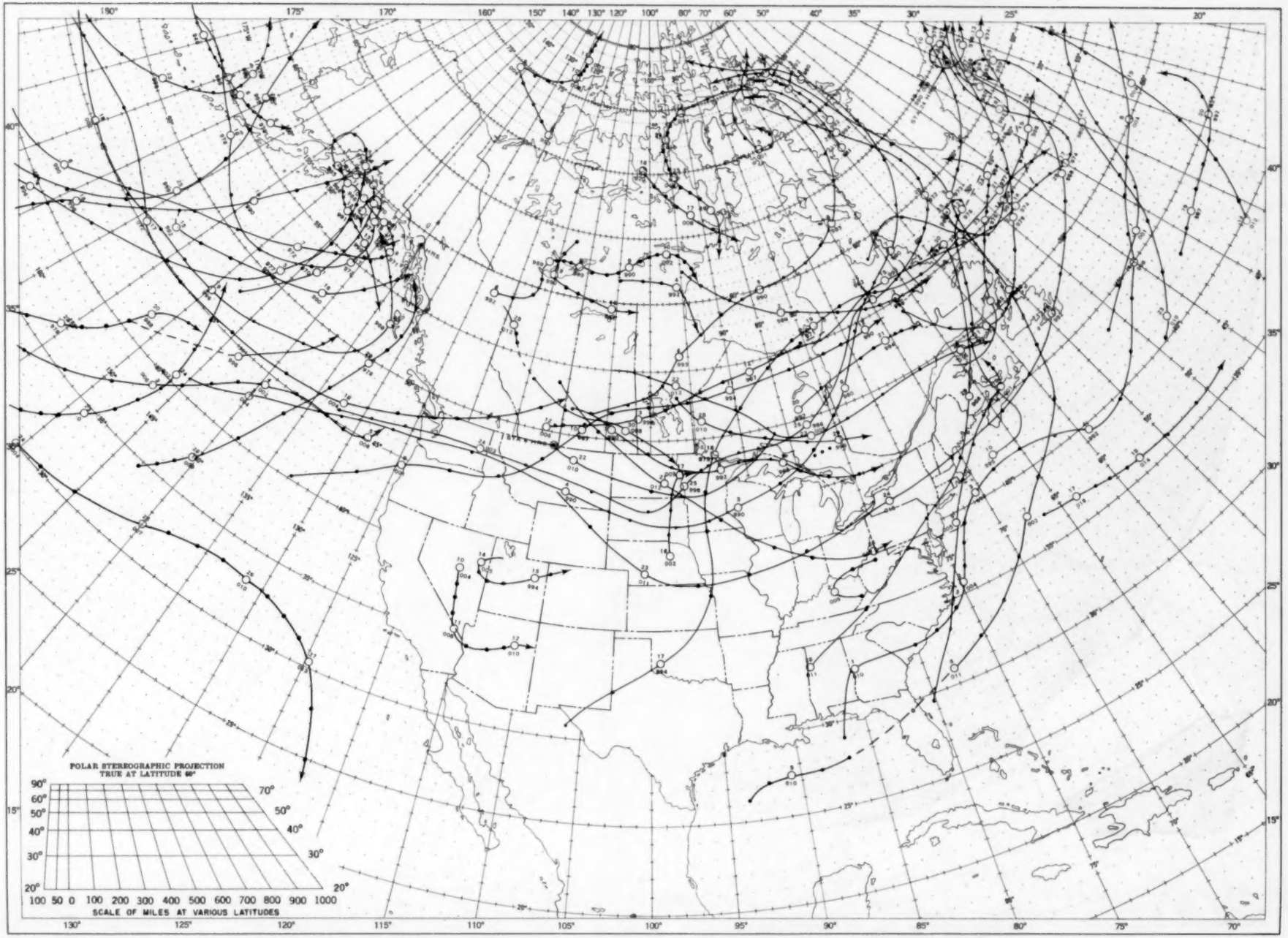
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, November 1958.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

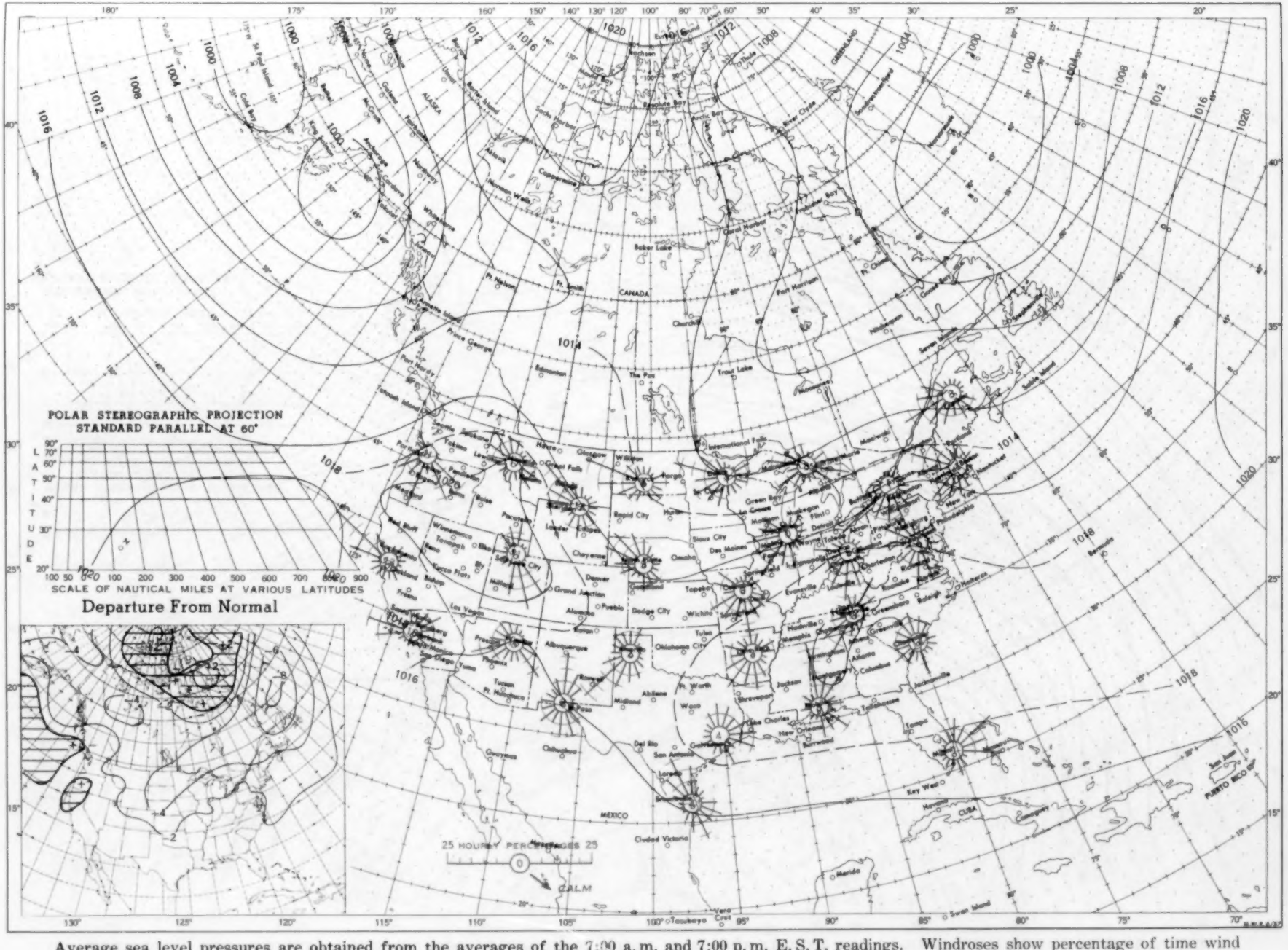
Circle indicates position of center at 7:00 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, November 1958.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

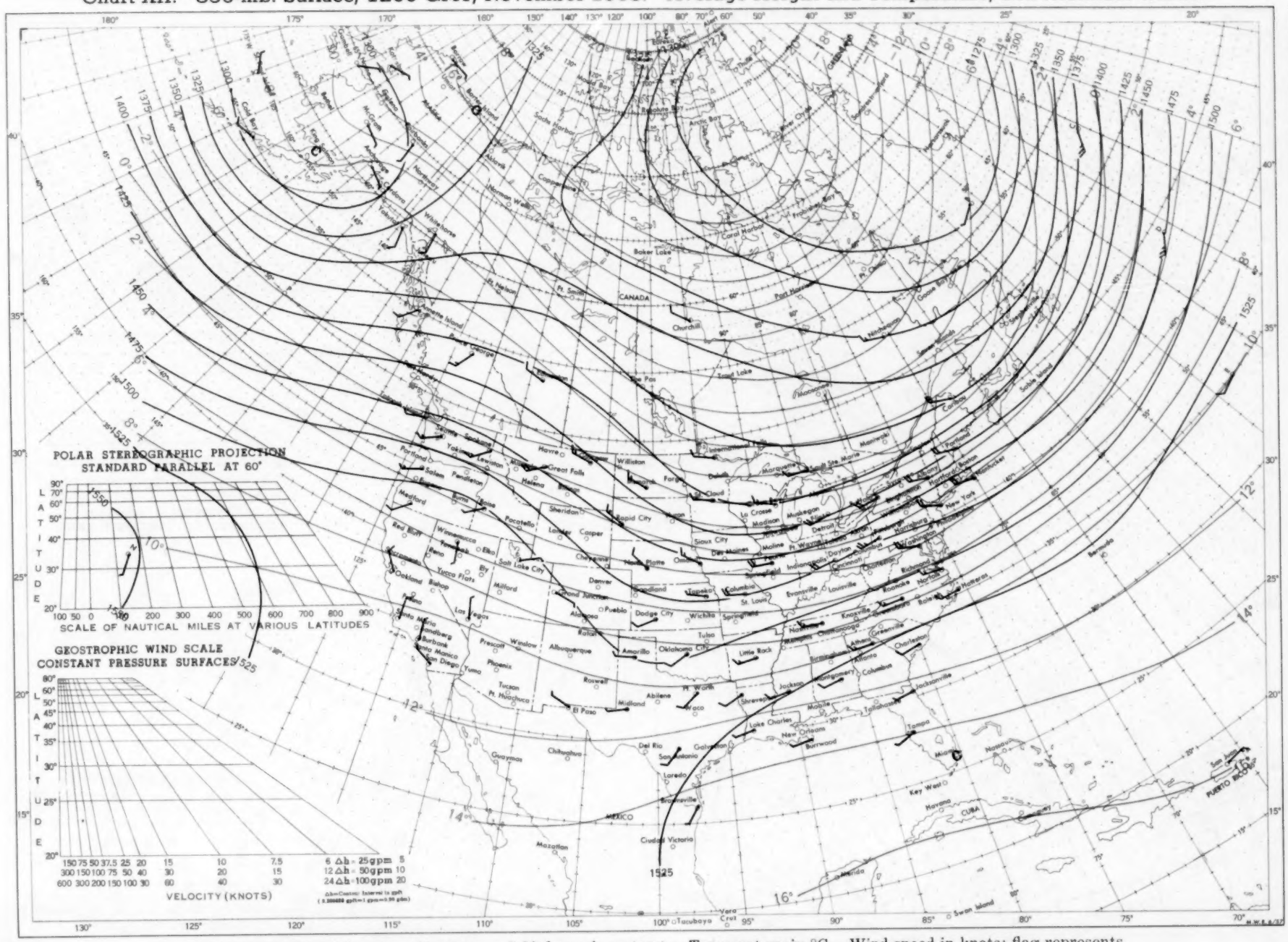
Circle indicates position of center at 7:00 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, November 1958. Inset: Departure of Average Pressure (mb.) from Normal, November 1958.



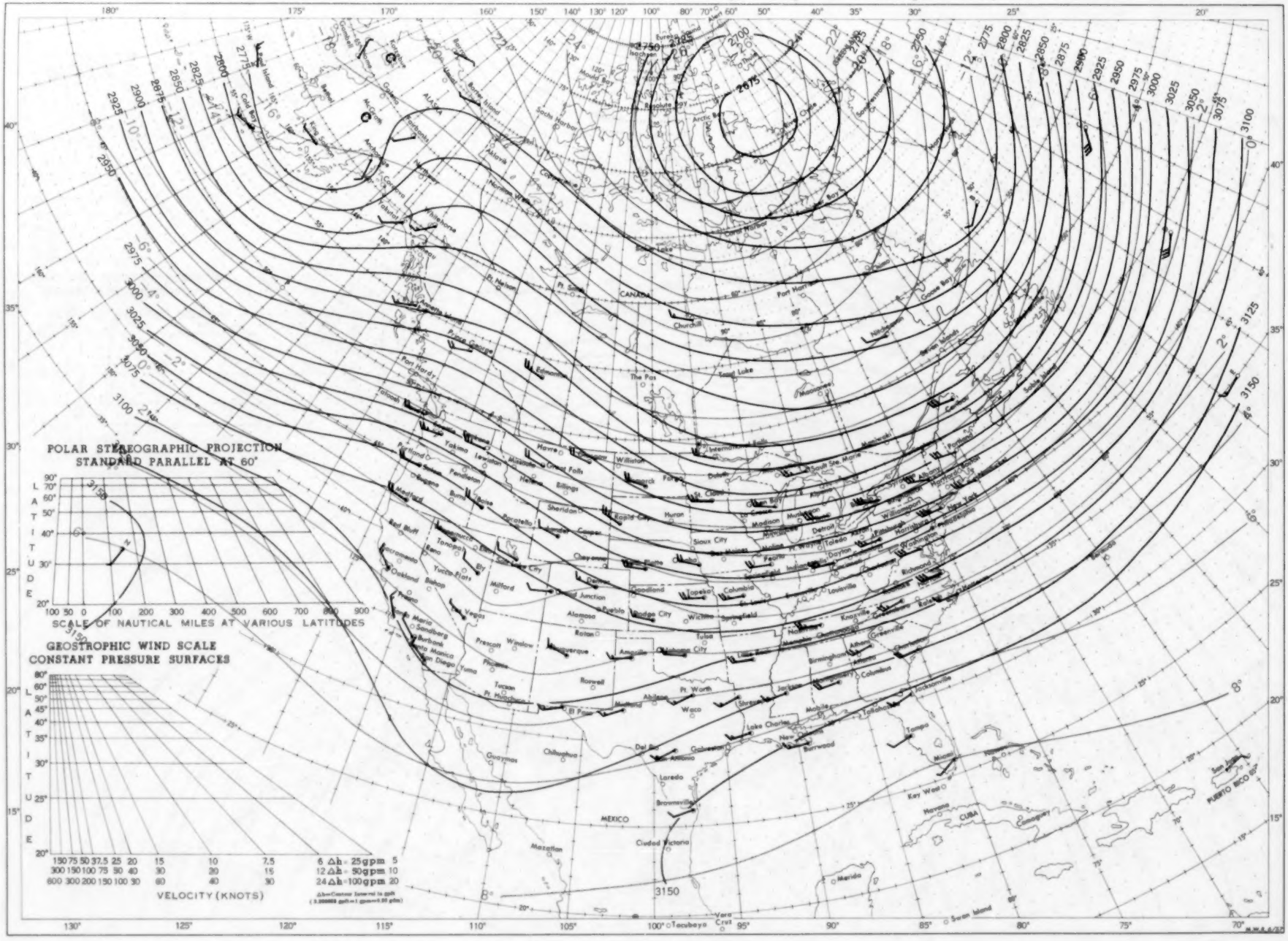
Average sea level pressures are obtained from the averages of the 7:00 a.m. and 7:00 p.m. E.S.T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 1200 GMT, November 1958. Average Height and Temperature, and Resultant Winds.



Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. All wind data are based on rawin observations.

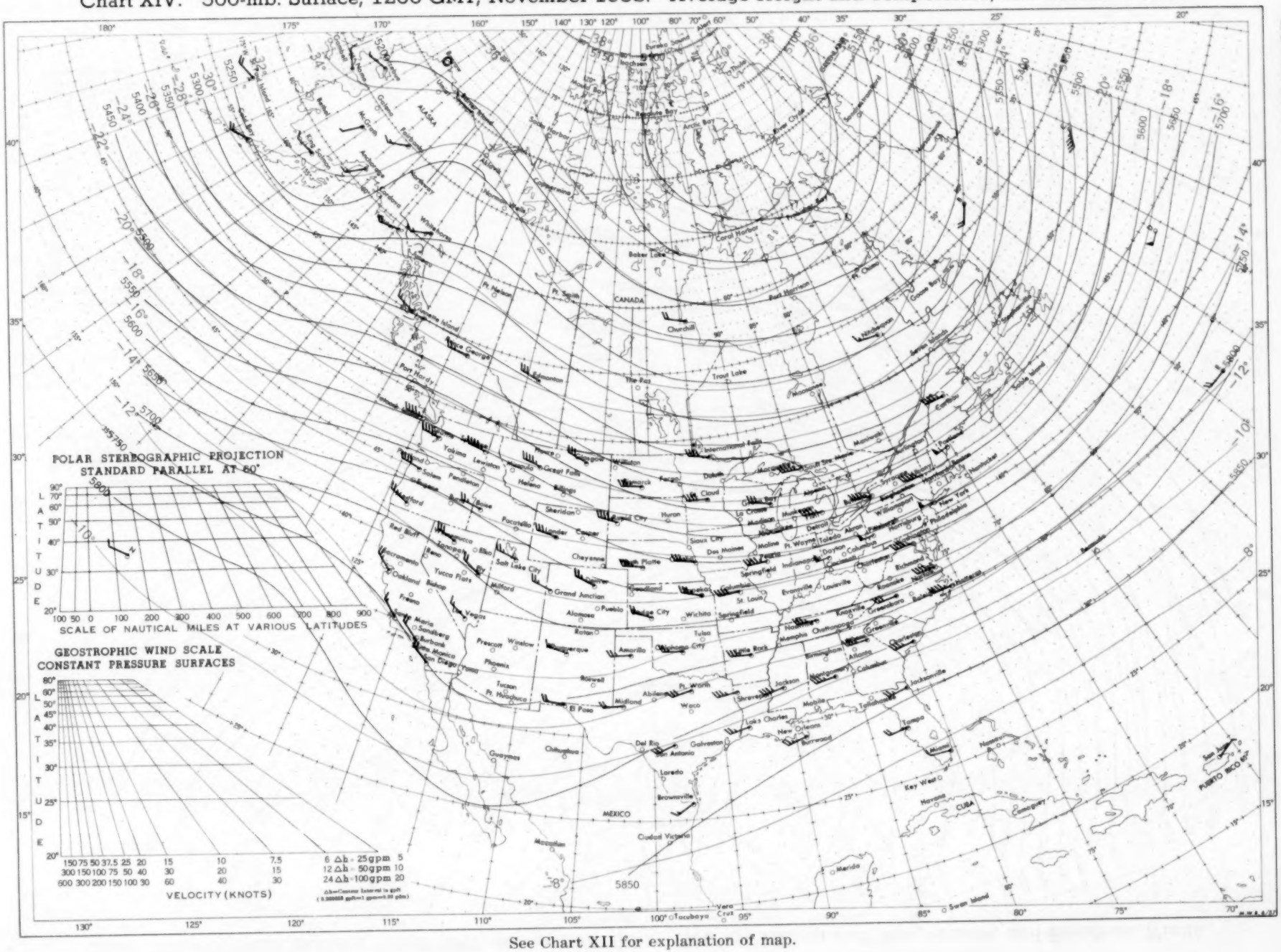
Chart XIII. 700-mb. Surface, 1200 GMT, November 1958. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

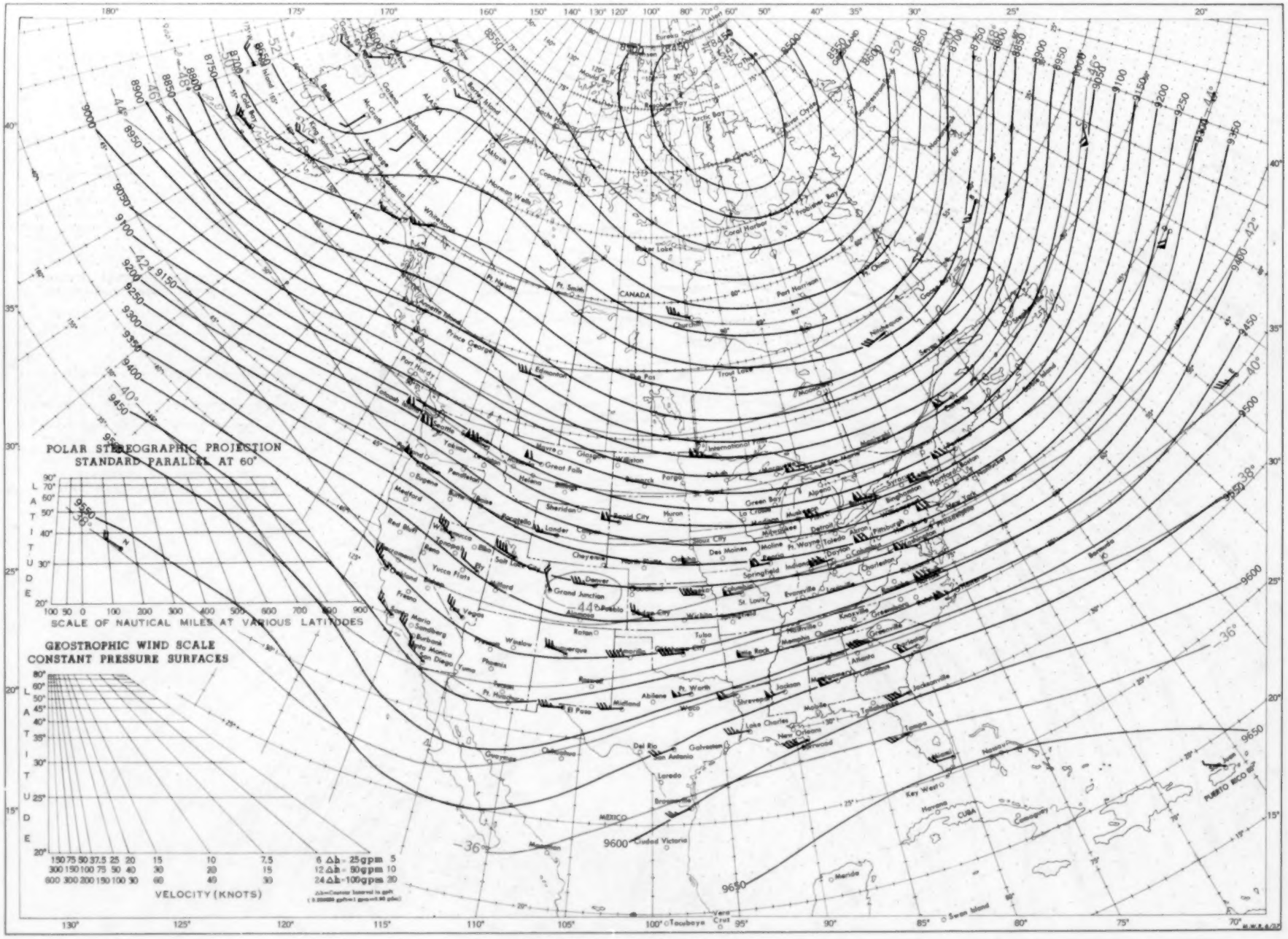
NOVEMBER 1958

Chart XIV. 500-mb. Surface, 1200 GMT, November 1958. Average Height and Temperature, and Resultant Winds.



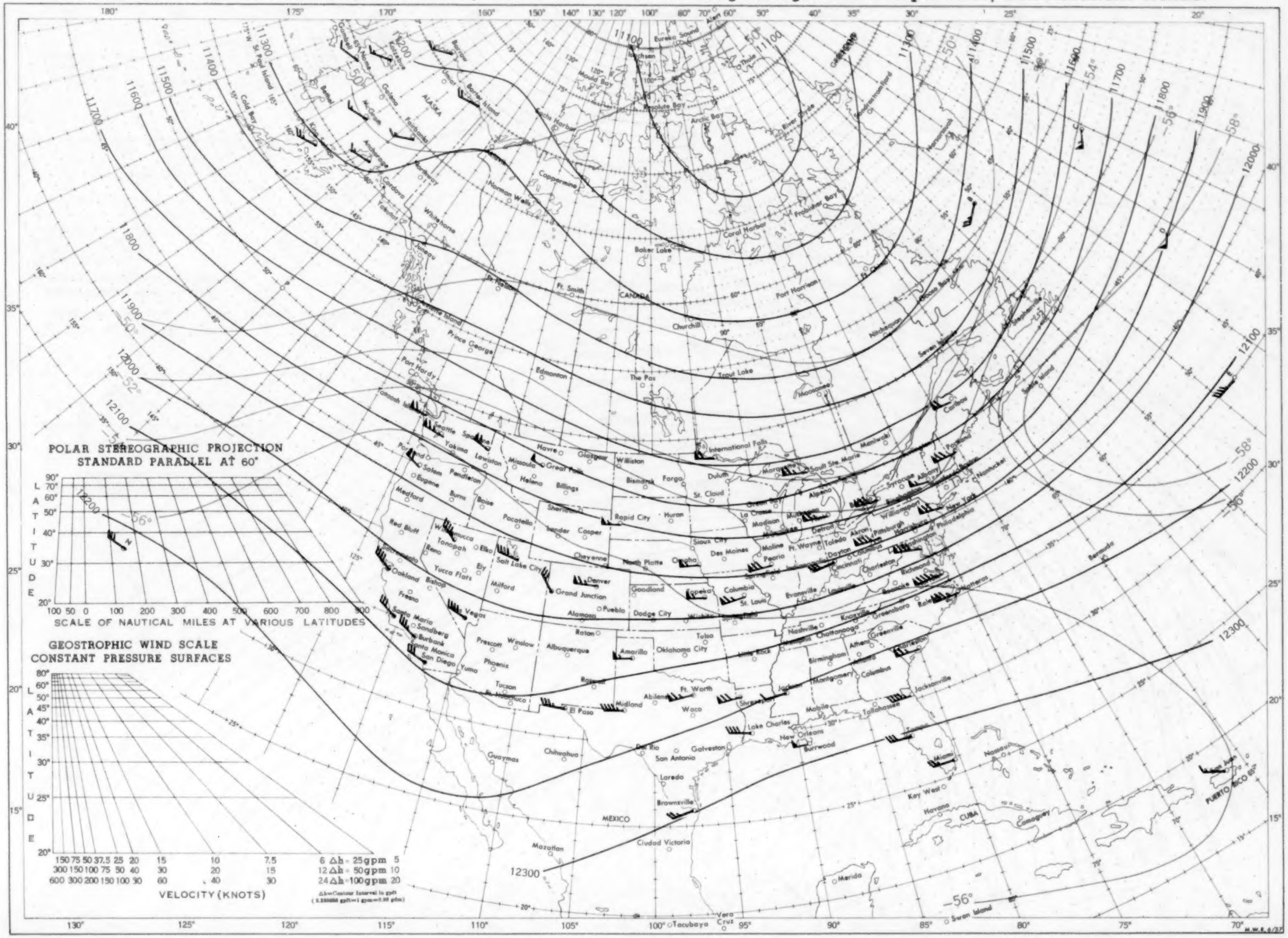
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 1200 GMT, November 1958. Average Height and Temperature, and Resultant Winds.



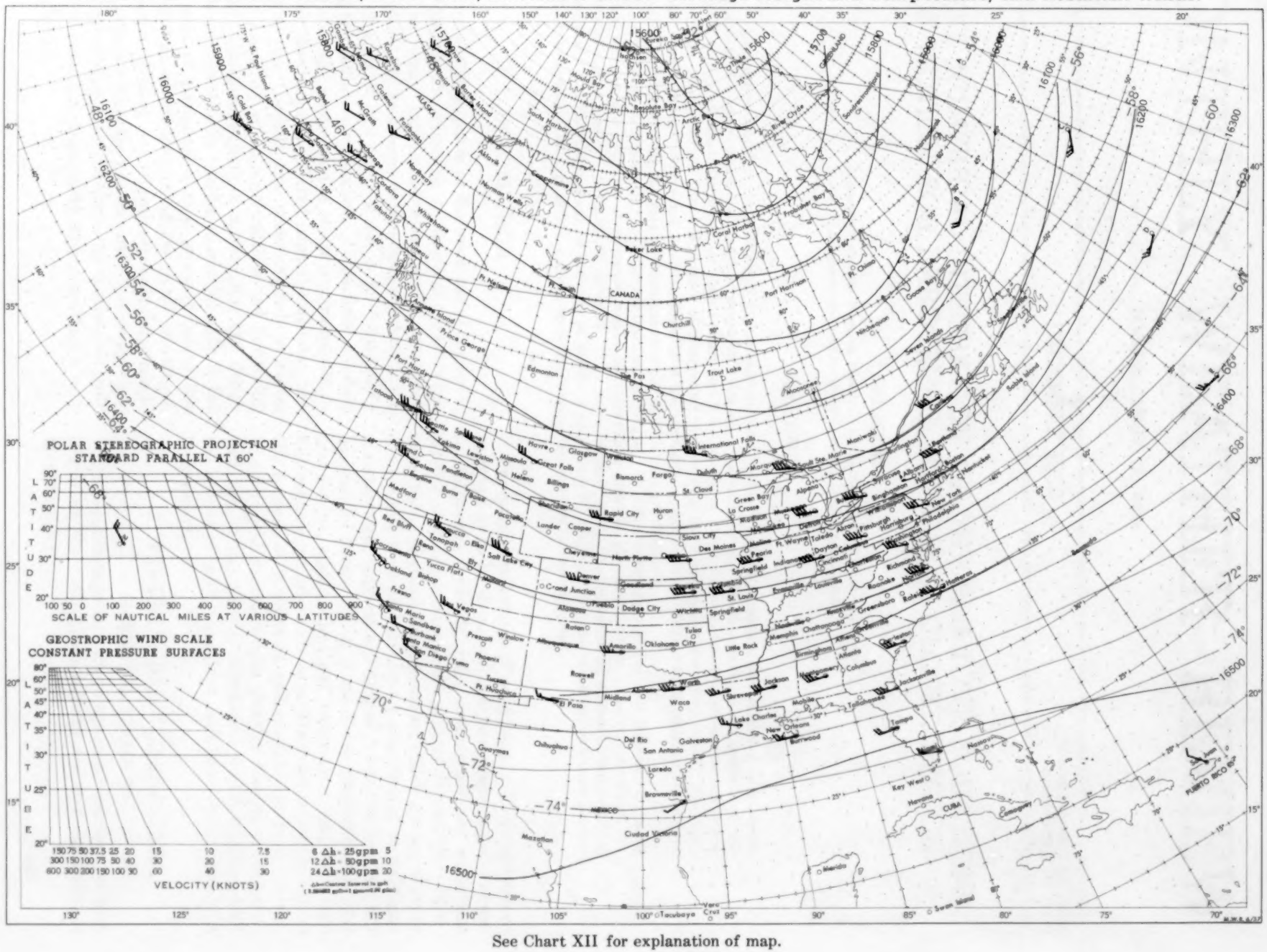
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 1200 GMT, November 1958. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

Chart XVII. 100-mb. Surface, 1200 GMT, November 1958. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

NOVEMBER 1958